U.S. DEPARTMENT OF COMMERCE
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PB-292 748

Assessment of the Use of Fugitive Emission Control Devices

Research Triangle Inst, Research Triangle Park, NC

Prepared for

Industrial Environmental Research Lab, Research Triangle Park, NC

Feb 79

United States
Environmental Protection
Agency

Industrial Environmental Research
Laboratory
Research Triangle Park NC 27711

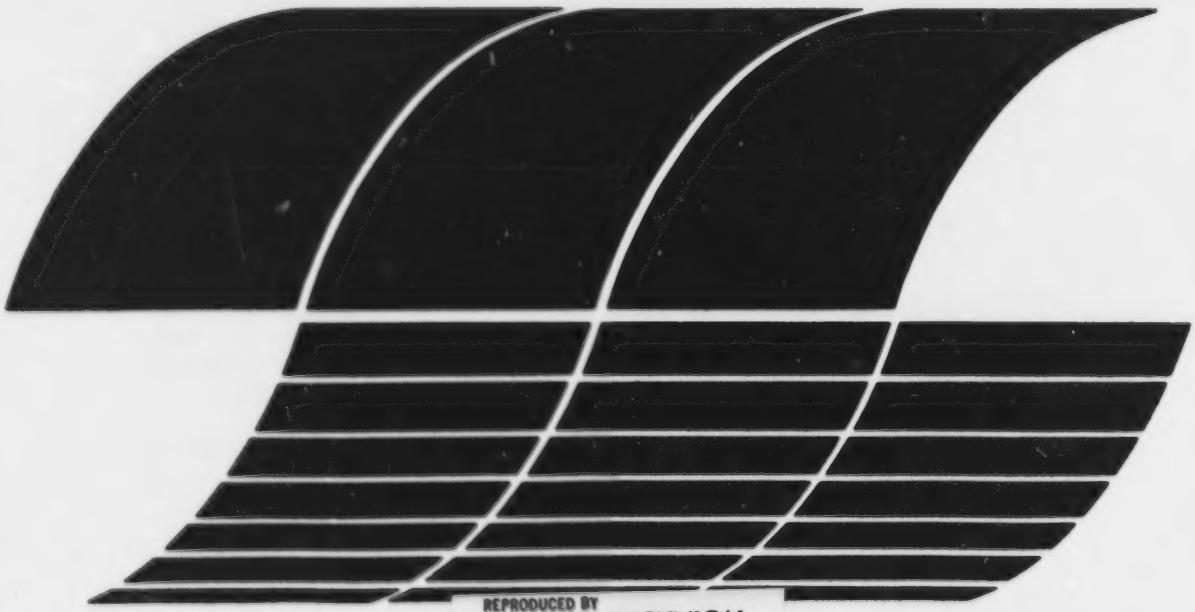
EPA-600/7-79-045
February 1979

PB 292748

EPA

Assessment of the Use of Fugitive Emission Control Devices

Interagency Energy/Environment R&D Program Report



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TECHNICAL REPORT DATA
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1. REPORT NO. EPA-600/7-79-045	2.
3. RECIPIENT'S ACCESSION NO. PB292748	
4. TITLE AND SUBTITLE: Assessment of the Use of Fugitive Emission Control Devices	5. REPORT DATE: February 1979
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S): D. P. Daugherty and D. W. Coy	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Research Triangle Institute, P.O. Box 12194, Research Triangle Park, North Carolina 27709	10. PROGRAM ELEMENT NO. EHE624
	11. CONTRACT/GRANT NO. 68-02-2612, Task 48
12. SPONSORING AGENCY NAME AND ADDRESS: EPA, Office of Research and Development, Industrial Environmental Research Laboratory, Research Triangle Park, NC 27711	13. TYPE OF REPORT AND PERIOD COVERED: Task Final: 2-12/78
	14. SPONSORING AGENCY CODE: EPA/600/13

15. SUPPLEMENTARY NOTES: IERL-RTP project officer is Dennis C. Drehmel, MD-61, 919/541-2925.

16. ABSTRACT: The report compares the efficiencies and utility consumptions expected from three fugitive emission control techniques--building evacuation, charged fog sprays, and water sprays with additives--if they were applied in primary lead and copper smelters. Estimates are provided of the reduction of total suspended particulate emissions and the reduction of elemental lead emissions from smelters when fugitive control is applied. Charged fog water sprays are emphasized: they enhance particulate collection by putting an electrostatic charge on fine water droplets. Building enclosure and evacuation is used as a basis with which such water sprays are compared. Available cost and energy consumption data were used to assess the competitiveness of charged fog sprays. Charged fog sprays were found to be less efficient than building evacuation, but also less expensive and less energy intensive by about a factor of 10. Charged fog sprays cannot replace conventional smelter techniques (e.g., secondary hooding or building evacuation) because they are not suitable for the typical large-volume, high-temperature, turbulent air streams. They are better suited for smaller scale, localized emission sources (e.g., conveyor transfer points) which contribute only a fraction of the fugitive particulate emissions.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Fogging	Pollution Control	13B	
Dust	Spraying	Stationary Sources	11G	07A
Aerosols	Additives	Fugitive Emissions	07D	
Leakage	Lead	Particulate		07B
Processing	Copper	Charged Fog Sprays	13H	
Evacuating	Smelters	Water Sprays		11F
	Electrostatics			20C

18. DISTRIBUTION STATEMENT: Unlimited	19. SECURITY CLASS (*This Report*): Unclassified	21. NO. OF PAGES: 86
	20. SECURITY CLASS (*This page*): Unclassified	22. PRICE: PC A05 MF A01

EPA Form 2220-1 (9-73)

EPA-600/7-79-045

February 1979

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by

D.P. Daugherty and D.W. Coy

Research Triangle Institute
P.O. Box 12194
Research Triangle Park, North Carolina 27709

Contract No. 68-02-2612
Task No. 48
Program Element No. EHE624

EPA Project Officer: Dennis C. Drehmel

Industrial Environmental Research Laboratory
Office of Energy, Minerals, and Industry
Research Triangle Park, NC 27711

Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Washington, DC 20460

ACKNOWLEDGEMENT

This report presents the results of a study conducted under EPA Contract 68-02-2612, Task 48. The research was conducted in the Industrial Process Studies Section of the Energy and Environmental Research Division of the Research Triangle Institute (RTI).

RTI acknowledges the time and courtesy extended by St. Joe Lead Company during a visit to their Herculaneum, Missouri smelter and, equally, the consideration shown by Kennecott Copper Corporation during a vist to their Hayden, Arizona smelter. The Ransburg Corporation and Dr. Stuart Hoenig of the University of Arizona at Tuscon provided useful information on charged fog spray devices.

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1.0 INTRODUCTION AND SUMMARY

Emissions from stacks and other so-called "point sources" have, in the past, been the main target of pollution control efforts. Windblown losses from storage piles, dust from material handling, fumes from hot metal transfer, and many other sources in the metals industry are not considered point sources. Instead, pollutants from these diffuse, non-ducted sources are termed "fugitive emissions." This report compares three fugitive control techniques--building evacuation, charged fog sprays, and water sprays with additives--as they might be applied in lead and copper smelters.

Fugitive emissions from lead and copper smelters have serious impacts on more than just the total suspended particulate levels; they may also contain toxic metals for which separate ambient standards exist or are being contemplated. The report estimates (from admittedly rough base-data) the reduction of total suspended particulate emissions and the reduction of elemental lead emissions from smelters when fugitive control is applied. Primary lead and copper smelters are considered; secondary smelters are not.

The control techniques of charged fog water sprays are emphasized in this report. (These sprays enhance particulate collection by putting an electrostatic charge on fine water droplets.) Building enclosure and evacuation is used as a basis with which such water sprays are compared. Secondary hooding is not evaluated as a control method, as it is being studied by others.[1]

Several limitations on the scope of this project need to be mentioned. No sampling was done to measure fugitive emission rates or compositions; values used in the report are cited from prior publications. Likewise, even though a copper smelter and a lead smelter were visited to discuss using charged fog sprays with plant engineers, there were no field trials as part of this project. Instead, available cost and energy consumption data was used to assess whether charged fog sprays are competitive with other devices.

Charged fog sprays are only beginning to be commercially applied; a small version with a maximum spray rate of 0.25 gpm is now commercially available.

No independent test data of charged fog spray efficiencies in industrial applications have been presented to date. In general: (a) while for uncharged sprays, there is a minimum in the collection efficiency for about two micron diameter particles, there is not any such minimum for charged sprays and some improvement in collection of respirable dust is expected from charging; (b) the charged fog sprays are best suited to localized sources of dust, suspended in a low velocity or stationary gas stream; (c) the combination of high temperatures and excessive gas turbulence rules out charged fog sprays for areas such as copper converter leakage or furnace taphole emission control; and (d) at reasonable water application rates, the charged fog sprays are unlikely to have efficiencies approaching 90 percent--overall collection efficiencies on the order of 50-60 percent are more likely.

Capital costs, utility requirements, and control efficiencies were estimated for both building evacuation and charged fog spray control techniques. The results are summarized in Table 1. Note that the reduction of fugitive emissions cited are on the basis of total fugitive emission including open source emissions such as windblown dust which are outside the control of either a building evacuation system or a charged fog spray. The efficiencies for sources within the control of building evacuation or charged sprays were taken as 95 percent and 60 percent, respectively.

While both capital investment and energy consumption are higher for building evacuation, the reduction of total particulate and elemental lead emissions are also greater for building evacuation because of the higher collection efficiency and the larger number of sources covered by a building evacuation system. About 10 to 20 k$ are required for each percentage reduction in emissions by spray versus 100 to 200 k$ required for each percent reduction for building evacuation. Similarly the electrical requirement is much lower for the charged fog sprays--15 to 30 kW for each percentage reduction versus 150 to 200 kW for the building evacuation system.

However, in spite of the apparent attractiveness of charged fog sprays, the authors feel that there are several practical problems which prevent them from supplanting building evacuation or secondary hooding as fugitive control techniques. The first and main objection is their limited applicability. Water sprays are only suitable when the process can tolerate water, when the

TABLE 1. SUMMARY OF CHARGED FOG SPRAY COMPARISON WITH BUILDING EVACUATION

Item	Lead Smelting	Copper Smelting
Reduction in fugitive total particulate emissions		
by application of charged sprays	30%	20%
by application of building evacuation	45%	40%
Reduction in fugitive elemental lead emissions		
by application of charged sprays	40%	35%
by application of building evacuation	75%	65%
Estimated capital investment		
for application of charged sprays	311 k$	366 k$
for application of building evacuation	8,683 k$	6,808 k$
Electrical requirement		
for application of charged sprays	417 kW	450 kW
for application of building evacuation	9,000 kW	6,000 kW

emissions are from localized sources, when there is not a great deal of air turbulence and when the air is not at high temperatures. These limitations rule them out for such major sources of fugitive emissions as converter leakage, sintering discharge, and metal tapping, pouring, and casting.

A second major limit on charged fog spray control is the collection of the agglomerated particles. It is usually assumed that once suspended particles collide with a water droplet, they are permanently removed from the atmosphere. This is a valid assumption for such applications as conveyor transfer points in moderately sill air where the agglomerated dust settles out and is returned to the process. However, when particles from, say, a railcar unloading station are contacted with spray droplets, they may settle out on the ground, dry out, and be reentrained. Particle control has only been temporary. The severity of this phenomenon is a major uncertainty for future large scale industrial applications of charged fog sprays.

It makes more sense to consider charged sprays and building evacuation as complementary control devices instead of mutually exclusive techniques.

Per high temperature, large scale, turbulent emissions, either building evacuation or secondary hooding are required to collect the fugitive emissions. Charged fog sprays are better suited for smaller, localized emission sources. Two applications for which charged sprays may be particularly advantageous over other controls are: (a) mobile sources such as front-end loaders (where any other type of control is impossible), and (b) areas such as sanders or grinding wheels where personnel exposure must be reduced without impeding access.

Water sprays with surfactant additives can be used to reduce dust entrainment from hard-to-wet solids, but have an advantage over conventional water sprays only for reducing dust generation from dusts which have not already been suspended. Surfactants do not substantially improve the collection of particles which have already become airborne. Thus, they are not substitutes for charged fog spray applications. The addition of surfactants or other additives should be considered for such applications as conveying and storage bins where the product is not water sensitive and can be kept moist to reduce dust entrainment from the solid. Additives other than surfactants may be used in some cases to form a "crust" on storage piles, etc., and reduce windblown resuspension of dust.

More detailed discussions of the material above, together with information on the smelting processes and the composition and amount of fugitive emissions are presented in the main body of this report.

2.0 CONCLUSIONS AND RECOMMENDATIONS

For equivalent degrees of control, charged fog sprays require roughly one-tenth the capital investment and utility requirement of building evacuation. However, the nature of charged fog sprays limit them to a maximum of 50-60 percent collection efficiency versus 95 percent for building evacuation.

The charged fog sprays are not expected to perform well in high temperature, very turbulent, open areas encountered in many of the major sources of smelter fugitive particulates: converter leakage, sintering discharge, and hot metal tapping and handling.

There is no data currently in the public domain regarding the efficiency of charged fog sprays in industrial environments. The device cannot be considered, at this point, established technology. The next logical step in development of the product is independent testing done on some industrial application of the sprays. This testing would define and document the performance of this device outside the laboratory. Several questions regarding its performance in evaporating conditions, cross-drafts, and rigorous environments need to be answered. Should the initial tests prove favorable, other applications such as spray curtains or mobile charged spray devices could be evaluated.

It is recommended that field evaluation and sampling of the charged fog spray device in an industrial application be conducted as a follow-up of this study. The estimated time required for such a sampling program is one man year.

3.0 FUGITIVE EMISSION SOURCES, RATES, AND COMPOSITIONS

Primary lead and primary copper smelting are discussed separately in this section. The sources, rates, and compositions of fugitive particulate emissions are discussed for both. Neither stack emissions nor fugitive gaseous emissions such as SO_2 are included. The study was limited to smelter operations between ore receipt and the casting of crude metal ingots.

The smelting processes are described briefly, emphasizing factors which alter the amount or composition of fugitive particulates. Although no single flowsheet can represent the variations between smelters, technology most common to United States smelters has been depicted. After this, the best available data for fugitive emission rates, by processing step, are discussed. Sadly, even the best estimates for rates are just that and not very reliable--few sources have been measured, and the measurement techniques for fugitive emissions only yield rates accurate within a factor of two to five.[2] Emission rates are presented solely as a basis for comparing control devices; in this use, inaccuracy in their measurement does not obviate the comparison.

Composition data for the fugitive emissions conclude the discussion of each smelting process. This data was obtained from several sources; references are given. This composition data was combined with source emission rates to yield Tables 2 and 3 which show the base rates of total particulate emissions and of elemental lead emissions. This pair of tables is later used in Section 7 to compare the emissions reduction from installing charged fog sprays with that obtained via building evacuation.

LEAD SMELTING

Process Description of Lead Smelting

Figure 1 depicts the lead smelting process steps commonly used in the United States to produce metallic lead from the concentrated ore. The figure is presented to acquaint the reader with the operations in primary lead smelting. Several sources were used to develop this flowsheet.[3-7] It represents no single smelter, but instead is a composite of the operations in several

TABLE 2. SUMMARY TABLE—BASIS FOR TOTAL PARTICULATE AND ELEMENTAL LEAD FUGITIVE EMISSION RATES:[a,b]

PRIMARY LEAD SMELTER, 100,000 METRIC TONS PER YEAR

Source of Fugitive Emission	Total Particulate Fugitive Emissions		Elemental Lead Fugitive Emissions	
	Operating Parameter metric tons/yr	Uncontrolled Emissions metric tons/yr	Weight Fraction Lead Contained in Emission	Uncontrolled Lead Emissions metric tons/yr
1. Railroad car and truck unloading				
Limestone	Limestone unloaded 39,700	4	0	0
Silica sand	Silica unloaded 1,800	0.19	0	0
Lead ore concentrate	Lead ore unloaded 158,900	17	0.60	10.2
Iron ore	Iron ore unloaded 22,500	2.5	0	0
Coke	Coke unloaded 47,200	9.5	0	0
2. Blast furnace flue dust				
a. Storage	–	Negligible	–	0
b. Handling and transfer	–	Negligible	–	0
3. Limestone				
a. Storage				
Loading onto pile	Limestone loaded 39,700	1	0	0
Vehicular traffic	Limestone stored 39,700	2.5	0	0
Loading out	Limestone loaded out 39,700	1	0	0
Wind erosion	Limestone stored 39,700	2	0	0
b. Handling and transfer	Limestone handled 39,700	4	0	0
4. Silica sand				
a. Storage	Silica stored 1,800	0.5	0	0
b. Handling and transfer	Silica handled 1,800	0.5	0	0
5. Lead ore concentrate				
a. Storage	Concentrate stored 158,900	26	0.60	15.6
b. Handling and transfer	Concentrate handled 158,900	264	0.60	158
6. Iron ore				
a. Storage	Ore stored 22,500	14.5	0	0
b. Handling and transfer	Ore handled 22,500	22.5	0	0
7. Coke				
a. Storage	Coke stored 47,200	3.5	0	0

See footnotes at end of table.

TABLE 2. (cont'd)

Source of Fugitive Emission	Total Particulate Fugitive Emissions: Operating Parameter metric tons/yr	Total Particulate Fugitive Emissions: Uncontrolled Emissions metric tons/yr	Elemental Lead Fugitive Emissions: Weight Fraction Lead Contained in Emission	Elemental Lead Fugitive Emissions: Uncontrolled Lead Emissions metric tons/yr
7. Coke (continued)				
b. Handling and transfer	Coke handled 47,200	4	0	0
8. Mixing and pelletizing	Lead produced 100,000	114	0.40	45.6
9. Sinter machine	Sinter produced 349,979	58	0.40	23.2
10. Sinter return handling	Sinter produced 175,000	788	0.40	315
11. Sinter machine discharge and screens	Sinter produced 175,000	131	0.40	52.4
12. Sinter crushing[c]	–	c	–	c
13. Sinter transfer to dump area	Sinter transferred 175,000	17.5	0.40	7
14. Sinter product dump area	Sinter dumped 175,000	1	0.40	0.4
15. Charge car or conveyor loading and transfer of sinter	Blast furnace charge 238,600	61	0.40	24.4
16. Blast furnace—monitor (total)[d]	Lead produced 100,000	8	0.35	2.8
17. Lead pouring to ladle and transfer	Lead produced 100,000	47	0.50	23.5
18. Slag pouring[e]	–	e	–	e
19. Slag granulator and slag piling[f]	–	f	–	f
20. Dross kettle	Lead produced 100,000	24	0.25	6
21. Reverberatory furnace leakage	Lead produced 100,000	150	0.25	37.5
22. Lead casting	Lead produced 100,000	44	0.50	22
SUBTOTAL NOT INCLUDING RESUSPENDED DUST		1,823		744
23. Resuspended dust[g]		740		74
TOTAL FUGITIVE EMISSIONS		2,563		818

Footnotes

[a] Rates are only estimates to be used as a basis for comparing alternate control devices.

[b] Emission rates are from Reference 2, pp. 2-130 to 2-149 prorated by ½ to convert from 200 Mg/yr to 100 Mg/yr.

[c] Emissions for sinter crushing included in emissions from sinter machine discharge and screens.

[d] Emissions for charging, blow condition, and tapping included in total. Emission factor for upset not considered part of normal operating conditions and is not included in emission factor for the blast furnace roof monitor.

[e] Emissions for slag pouring included in lead pouring to ladle and transfer emission.

[f] Granulated slag is wet and, therefore, most likely not a source of fugitive emissions.

[g] Resuspended dust contributes additional 10 percent to elemental lead (Reference 13). Lead content of resuspended dust assumed to be 10 weight percent to calculate total resuspended dust.

TABLE 3. SUMMARY TABLE–BASIS FOR TOTAL PARTICULATE AND ELEMENTAL LEAD FUGITIVE EMISSION RATES.[a,b]

PRIMARY COPPER SMELTER 100,000 METRIC TONS PER YEAR

Source of Fugitive Emission	Total Particulate Fugitive Emissions		Elemental Lead Fugitive Emissions	
	Operating Parameter metric tons/yr	Uncontrolled Emissions metric tons/yr	Weight Fraction Lead Contained in Emission	Uncontrolled Lead Emissions metric tons/yr
1. Unloading and handling of ore concentrate[c]	Ore concentrate 337,000	1.690	0.0167	28.2
2. Ore concentrate storage				
Loading onto pile	Ore concentrate loaded 337,000	7.0	0.0167	0.11
Vehicular traffic	Ore concentrate stored 337,000	22.1	0.0167	0.37
Loading out	Ore concentrate loaded out 337,000	9.0	0.0167	0.15
Wind erosion	Ore concentrate stored	18.1	0.0167	0.31
3. Limestone flux unloading, handling, and storage	Limestone flux 153,000	25.4	0	0
4. Roaster charging[d]	–	d	–	0
5. Roaster leakage[d]	–	d	–	0
6. Calcine transfer[d]	–	d	–	0
7. Charging reverberatory furnace	Copper produced 100,000	425	0.015	6.38
8. Tapping of reverberatory[e]	–	e	0.015	e
9. Reverberatory furnace leakage[e]	–	e	0.015	e
10. Slag tapping[e]	–	e	0.015	e
11. Converter charging	Copper produced 100,000	602	0.020	12.0
12. Converter leakage[f]	–	f	0.020	f
13. Slag tapping from converter[f]	–	f	0.020	f
14. Blister copper tapping[f]	–	f	0.020	f
15. Blister copper transfer[f]	–	f	0.020	f
16. Charging blister copper to fire refining furnace	Copper produced 100,000	95	0.010	0.95
17. Copper tapping and casting	Copper produced 100,000	126	0.010	1.26
18. Slag tapping and handling[g]	–	g	0.010	g
SUBTOTAL NOT INCLUDING RESUSPENDED DUST		3,020		49.7
19. Resuspended dust[h]		2,013		1.0
TOTAL FUGITIVE EMISSIONS		5,033		50.7

Footnotes

[a] Rates are only estimates to be used as a basis for comparing alternate control devices.

[b] Emission rates are from Reference 2, pp. 2-115 to 2-129.

[c] Also includes slag handling.

[d] Emissions from roaster charging, leakage, and transfer are not included because of clean natures of newer roasting processes (e.g., Fluosolids).

[e] Emissions from reverberatory tapping and leakage are included in emission factor for reverberatory charging.

[f] Emissions from converter leakage and tapping, and blister copper transfer are included with converter charging emission factor.

[g] Emissions from slag to tapping are included in casting building emissions.

[h] A resuspended dust contribution of 40 percent of total emissions was assumed. Lead content of resuspended dust was assumed to be 0.05 weight percent (Reference 27).

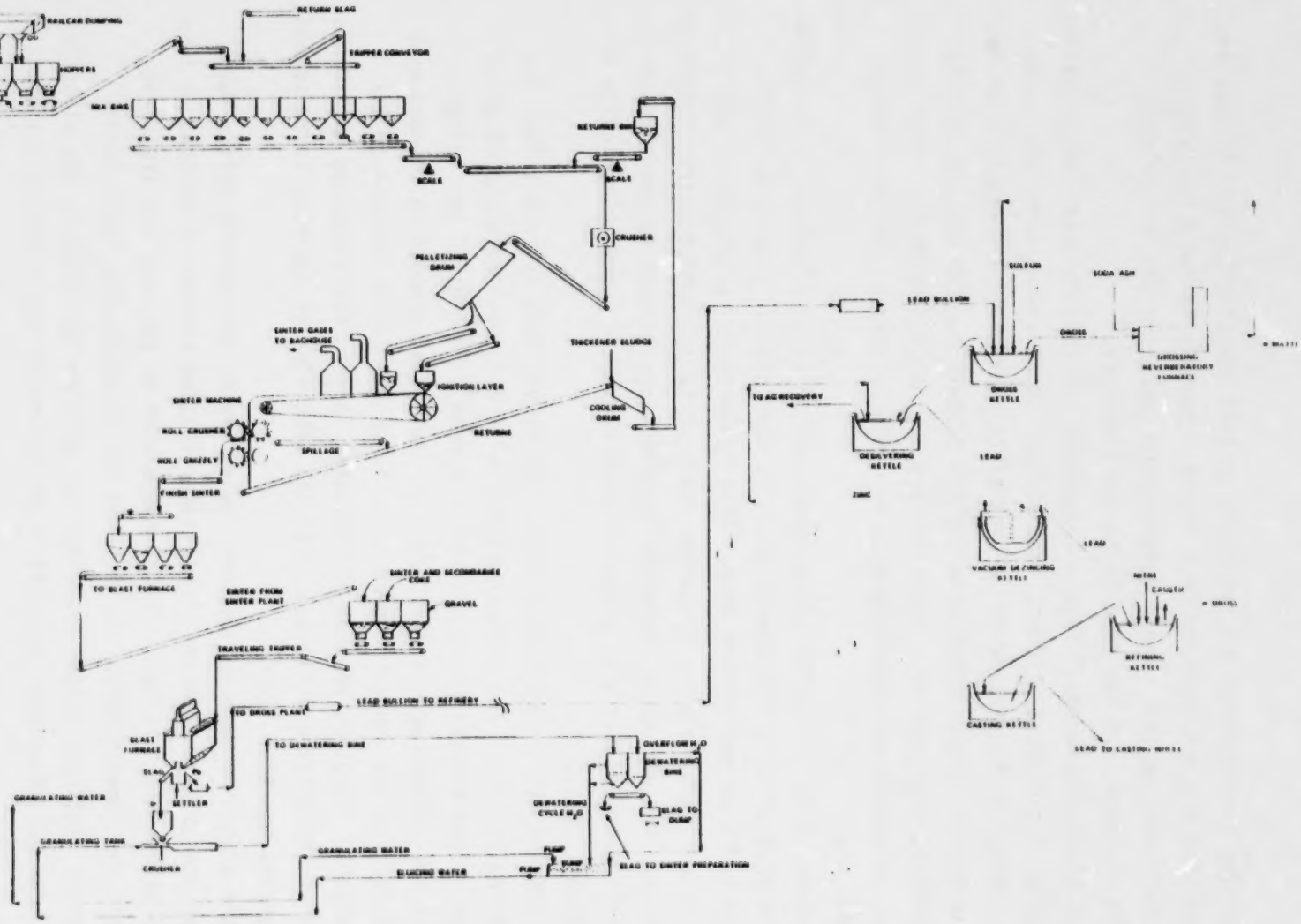


Figure 1. Flowsheet of Typical Lead Smelting Operations.

smelters. The purification and transport of lead smelting byproducts such as silver and zinc are not shown in this figure. Neither is the processing of lead ore into concentrate. Ore processing and concentration is typically handled at the mine, and has been discussed elsewhere.[8]

Manufacturing lead metal from a concentrate of sulfide ores (mainly galena, PbS) involves three steps. First, lead sulfide is converted into lead oxide and lead sulfate by burning 80-90 percent of the sulfur in the ore by a process called sintering. The oxidized lead (called sinter) is then reduced to metallic lead by heating with coke in a blast furnace. Finally, the molten crude lead is refined to remove any remaining metals--commonly copper, zinc, antimony, silver, and tin.

As mined, lead ore is not concentrated enough to be processed in a smelter. The ore is crushed to a fine powder which is concentrated via flotation to between 45 to 75 weight percent lead. This concentrate is shipped to the smelter via railcars, trucks, or barges where it is unloaded and transferred to storage bins. The unloading, material handling, and storage of concentrate is a potential source of fugitive emissions with high lead content (typically 60 weight percent lead.)

The concentrate is mixed with fluxes and return slag to make a feed for the sintering process. The sintering machine is a travelling grate on which the sulfur in the concentrate is partially burned. To control the sulfur content of the sinter machine feed, some of the sinter product is blended with the fresh feed to the sintering machine to lower the sulfur content to 5-7 weight percent. About 10 percent of the total feed to the sintering machine is laid down on the grate and ignited, with the remainder of the feed being spread on the burning ignition layer.

On the sintering machine, the heat generated by the burning sulfur fuses the sinter into a hard clinker. The clinker (called sinter) is crushed to less than five inches and screened. The coarse sinter is the feed for the blast furnace and the finer material is returned for blending with fresh feed.

Material handling, sinter crushing, and particulate escaping the sintering machine hoods all contribute to fugitive emissions in the sintering building.

Discussions with lead industry engineers indicated sintering and the associated crushing as probably the largest process source of fugitive particulate in lead smelting.[9]

In the next processing step, sinter, coke, and flux are charged to a blast furnace. The coke is consumed in the blast furnace and reduces the sinter to molten lead. Fresh sinter and coke are periodically added to maintain the furnace charge height. The molten mass in the furnace bottom is settled into a layer of molten lead and a lighter slag layer. The molten material may be tapped continuously or on an intermittent basis. Typically, the molten slag is granulated with a water jet and then dumped in open piles.

Fugitive emissions from the blast furnace are normally low, but may become significant during process upsets. The pressure at the top of the blast furnace normally is sufficiently low that gases passing up through the furnace are sucked into the central collection hood and do not enter the work space directly above the blast furnace. If the blast furnace charge is not porous enough, high pressures can build up across the furnace charge and in extreme circumstances blow particulate into the working area. Another problem occurs when a "blowhole" develops and the hot gases preferentially bypass the main body of the furnace charge through a channel which has formed. Very little visible fugitive particulates are seen from the slag granulation.

Most zinc originally present in the ore concentrate ends up in the blast furnace slag. When the economics so dictate, and the smelter has the proper equipment, the zinc can be recovered in a zinc fuming furnace. Only three of the six U.S. lead smelters have zinc fuming furnaces, and these operate intermittently, depending on the zinc market conditions. Fugitive emissions from zinc fuming furnaces have been reviewed in another report.[10] They are not considered in this report because most lead smelters do not have zinc fuming furnaces.

More variation is found in the refining areas of lead smelters than in the other two processing steps; refining is designed around the ore source available to the smelter. The content of copper and other trace metals varies between ores, but in general ores can be classified as Missouri or non-Missouri lead ores. Missouri lead ores contain traces of silver and cadmium, but little copper or others impurities. Accordingly, their refining is not as involved

as that for the more complex ores. Missouri lead ore accounts for over 80 percent of the ore mined in the U.S.[11] Accordingly, the following refining sequence is from a Missouri smelter.[5]

Molten lead bullion from the slag settler is moved through a series of 250 ton capacity, hemispherical refining kettles. First the bullion is transferred to a drossing kettle where sulfur and other additives are added and the metal is cooled. At about 430° (800°F), copper and other impurities solidify and are skimmed off and transferred to a reverberatory drossing furnace. In the drossing furnace, soda ash is melted with the dross and causes it to separate into (a) matte which is solidified and may be shipped to a copper smelter for recovery of the contained copper, and (b) lead bullion which is recycled to the drossing kettle. Impure lead from the drossing kettle is reheated in a desilvering kettle where zinc is added and a crust enriched in silver and gold is removed as the metal cools. To remove zinc remaining in the lead, a subsequent kettle fitted with a vacuum hood is used to vaporize zinc from the molten lead. As a final refining step, caustic soda and niter are added in a refining kettle. The remaining impurities rise to the surface and are skimmed off. The refined molten lead is then cast into pigs or ingots.

Fugitive emissions from the refining process consist mainly of fumes from molten metal handling.

There are several material handling operations in the smelter which have not been specifically mentioned above--an in-plant rail system is typically used to transport quantities of slag to the dump, baghouse dust to storage bins, and make other batch materials movements; the molten lead bullion is moved via ladle cars and overhead crane ladles; and slag, although usually granulated, may be moved in wheeled slag pots. The operation and movement of front-end loaders, trucks, and other vehicles can create fugitive dust emissions.

A final source of fugitive particulate, often neglected but quite important, is windblown dust resuspended from the ground, storage piles, or open areas around the smelter. In the integrated iron and steel industry, such open source fugitive emissions have been estimated to be roughly the same magnitude as fugitive emissions from process operations.[12]

Fugitive Emission Rate Data for Lead Smelting

Particulate emissions that are from fugitive (i.e., non-ducted) sources have not received the same level of study that point sources (i.e., stack emissions) have. Accordingly, emission rate factors for fugitive sources are not well established; few reliable measurements have been made. Available rate data is of questionable accuracy, but since the purpose of this report is to compare alternate control methods, rate data is presented and used as a base case for comparing charged fog sprays with building evacuation. Only with a clear understanding of its limitations should the data be used for any other purpose.

PEDCo Environmental, Inc.[3] has prepared a list of fugitive emission factors for a hypothetical 200k metric tons per year lead smelter. The average capacity in 1976 of the six United States primary lead smelters[11] was only about 100k metric tons per year, and the PEDCo factors have been prorated by one-half to prepare the emissions rates shown on Table 2. The smelting flowsheet used by PEDCo to estimate fugitive emission rates is not the same as that presented in Figure 1, but it is felt that the emission factors are not accurate enough to justify a complete recalculation of emission rates. Some modifications of the PedCo emission rates were made--the contribution from the silver retort building and the contribution of the zinc fuming furnace listed in the PEDCo tabulation are not included in Table 2. Also, a contribution from particulate resuspended from open areas was added.

TRC[13] has pointed out that there may be a large contribution from resuspended particulate deposited on the plant grounds. They estimated the effect of resuspended particulate by comparing ambient lead measurements from periods of normal smelter operation with those from times when the smelter was shut down because of strike or holiday. Their data are summarized in Table 4 and are the basis of the resuspended dust contribution added to the fugitive emissions inventory. Table 4 data indicate that about an additional 10 percent contribution to elemental lead (not total particulate) is made by resuspended particulate. For the source inventory in Table 1, this resulted in an extra 74 metric tons per year of elemental lead. To get an estimate of the total suspended particulate contributed by resuspension, the 74 metric tons per year

TABLE 4. RELATIVE CONTRIBUTIONS FROM VARIOUS EMISSION SOURCES TO FENCELINE CONCENTRATIONS OF AMBIENT LEAD AT PRIMARY LEAD SMELTERS*

Plant	Automobile $\mu g/m^3$	Resuspension $\mu g/m^3$	Stack plus fugitive[a] $\mu g/m^3$	Total $\mu g/m^3$	Resuspension as a percentage of total
Bunker Hill	0.5	4.6	10	15	46
ASARCO, El Paso	0.4	2.7	27	30	10
St. Joe	0.2	1.5/0.5[b]	8/16[b]	10/17[b]	19/3[b]
ASARCO, Glover	0.4	1.5[d]	15	17	10[c]

*Data is from Reference 13.

[a]The numbers presented represent long term averages (i.e., if two years of data are available, the value would be a two-year average). Individual monthly averages would range higher.

[b]Upwind data/Downwind data.

[c]Insufficient data were available for an accurate resuspension contribution. The number presented is based on the assumption that the fall-off rate is similar to that exhibited by the other plants.

of lead were converted to 740 metric tons per year of total particulate by assuming a lead content of 10 weight percent. It is recognized that this resuspended contribution is only a gross approximation. It is included to give a truer picture of the total fugitive emissions from a smelter.

Fugitive process emission measurements done by Constant et al.[6] are presented in Table 5. Their data considers fugitive emissions from an entire operation, such as from the individual processes of a sinter building, as one source.

Fugitive Emission Size and Composition Data for Lead Smelting

Several sources were used to obtain composition and size data for fugitive emissions. The compositions were used to calculate elemental lead emission rates from emission factors for total suspended particulates. This section discusses the origins of the composition data used in Table 2.

Galena (PbS) is the major lead-bearing mineral in the ore concentrate fed to lead smelters; pure galena contains 86.6 weight percent lead. Smelter concentrates vary from around 45 percent up to 75 percent lead and contain

TABLE 5. EMISSION FACTORS FOR LEAD SMELTING AS MEASURED BY MRI*

Operation	Total Emission Rate of Fugitive Particulate	
	Glover, MO Plant Mg/y	East Helena, MT Plant Mg/y
Sinter Building	19.4	10.3
Blast Furnace	19.5	5.5
Dross Kettles	---	47.6[b]
Reverberatory Furnace	---	
Ore Storage Bins	1.3	---
Plant Total	40.2	63.4[b]

*Yearly emission rates were calculated from lb/day data in Reference 6 assuming 350 d/yr of smelter operation.

[a]Average of dross kettles and reverberatory furnace.

[b]Total does not include 2.2 Mg/yr from a zinc fuming facility or 5.3 Mg/yr from a zinc furnace which were listed in Reference 6.

varying amounts of minor impurities depending on the ore source. Table 6 shows the range of lead concentrate compositions cited in the referenced articles. Sixty percent lead was used in Table 1 for fugitive emissions from concentrate handling. No lead enrichment in these fugitive emissions is expected, since the ores have not yet been exposed to temperatures which might produce fume that is enriched in volatile metals.

The lead content of fugitive emissions around the sintering machine was taken as 40 weight percent based on the data in Table 7. Note that the final two columns in Table 7 given compositions of fugitive emissions from two sintering buildings as measured in Reference 6. (There are three values mentioned for lead content of sintering building emissions in Reference 6: 58 percent in Table 11; 27.5 percent in Table 10; and 34.5 percent calculated from Table 8. The mid-value has been shown.)

For lead contents in other operation areas, Table 8 of this report presents sampling data from Reference 6. As is seen, there is little consistency in the numbers. In this report, the authors have: (a) used 35 weight percent lead for fugitive emissions from the blast furnace area, since about 10

TABLE 6. LEAD CONCENTRATE COMPOSITIONS

Constituent	Weight Percent Unless Otherwise Specified				
	Reference 8	Reference 14	Reference 15	Reference 7	Reference 17
Pb	45-60	55-70	70	72	76.1
S	10-30	13-18.5	No Data	No Data	15.6
Zn	0-15	0-6.5	1.5	0.8-2.9	1.0
Fe	1-8	0-5	No Data	No Data	3.9
Cu	0-3	0.5-4	0.5	0.9	0.04
CaO	tr-3.0	tr	No Data	No Data	0.25
As	0.1-0.4	tr	No Data	No Data	0.28
Sb	0.01-2.0	No Data	No Data	No Data	0.12
Bi	tr-0.1	No Data	No Data	No Data	0.04
Cd	tr	tr	0.2	No Data	No Data
Ag	0-50 oz/t	tr	No Data	1 oz/t	35 oz/t
Au	0-"few" oz/t	tr	No Data	No Data	0.48 oz/t

TABLE 7. COMPOSITION OF SINTERING EMISSIONS

CONSTITUENT	WEIGHT PERCENT UNLESS OTHERWISE SPECIFIED								
	FEED[a]	FEED[b]	FEED[c]	PRODUCT[c]	PRODUCT[b]	PRODUCT[b]	ROOF MONITOR[d]	ROOF MONITOR[e]	PRODUCT[f]
Pb	40-46	32.0	42.2	42.0	35.5	28-36	34.8	9.6	48
S	5-7	10.6	4.2	1.86	1.4	0.75-1.6	no data	no data	1.4
Zn	no data	5.6	3.6	3.93	10.0	9.5-12.5	no data	no data	no data
Fe	no data	9.4	no data	no data	9.7	12-15.5	no data	no data	12
Cu	no data	2.0	no data	no data	2.9	0.6-1.5	no data	no data	1
CaO	no data	4.5	no data	no data	10.3	9.0-10.5	no data	no data	5
As	no data	no data	0.38	0.36	no data	no data	0.033	0.79	no data
Cd	no data	0.05	0.0020	0.0020	0.04	no data	no data	no data	no data
Ag	no data	30-150*	no data	no data	30-150*	10-21*	no data	no data	no data

[a] Reference 4, p. 3-183.
[b] Reference 8, p. 5-13.
[c] Reference 16, p. 39.
[d] Reference 6, p. 11.
[e] Reference 6, p. 20.
[f] Reference 7.
* ounces/ton

TABLE 8. LEAD CONTENT OF FUGITIVE EMISSIONS FROM LEAD SMELTING OPERATIONAL AREAS*

Operation	Lead/Total Particulate
Glover, MO, plant	
Ore-storage-bin area	0.508
Blast-furnace area	0.498
Sinter building	0.275
Background at truck-to-rail ore transfer point	0.104
East Helena, MT, plant	
Background at ore loading	0.217
Dross/reverberatory building	0.222
Sinter building	0.096
Blast furnace	0.108

*Data is from Reference 6.

percent coke is added to the sinter which is initially 40 percent lead; (b) used 50 weight percent lead for fugitive emissions from lead transfer, ladling, and casting since furnace tapping measurements in Table 11 of Reference 6 averaged 52 percent lead; (c) eliminated slag cooling and piling from the emissions inventory under the assumption that all slag is granulated with negligible fugitive emissions; (d) eliminated zinc fuming emissions from the inventory; (e) used 25 weight percent lead for fugitive emissions from the drossing and reverberatory furnace operations, since a measurement[6] of this area was 22.2 percent; and (f) eliminated silver retorting emissions from the inventory.

Some size distribution data was found for fugitive emissions from lead smelters. Midwest Research Institute (MRI) conducted actual plant measurements of fugitive emissions from two ASARCO primary lead smelters: the Glover, Missouri plant and the East Helena, Montana plant.[6] Because of the measurement problems associated with individual sources, fugitive emissions from an entire operation (such as the sintering building) were measured as one fugitive source.

MRI determined the particle size range of total particulate fugitive emissions for four locations at the Glover plant: (1) sintering building, (2) blast furnace tapping area, (3) blast furnace feed charging area, and (4) ore

storage bin area. A Sierra, Model 230, HiVol cascade impactor was used. A Sierra impactor was also used to determine the particle size range for total fugitive emissions from the East Helena blast furnace operations. The results are summarized in Table 9.

TABLE 9. PARTICLE DISTRIBUTION FOR FUGITIVE PARTICULATES FROM LEAD SMELTING*

Location	Concentration $\mu g/m^3$	Concentration wt%	Particle size range μm
Sinter building, Glover, Missouri	1,420	66.18	<0.38
	207	9.64	0.38-0.71
	174	8.11	0.71-1.15
	112	5.22	1.15-2.3
	117	5.45	2.3-5.6
	116	5.40	>5.6
Blast furnace tapping operations, Glover, Missouri	44.1	17.19	<0.31
	39	15.20	0.31-0.59
	32.7	12.74	0.59-0.95
	24.7	9.62	0.95-1.9
	40.4	15.74	1.9-4.6
	75.7	29.51	>4.6
Blast furnace charge-feed area, Glover, Missouri	1,301	62.81	<0.33
	79.1	3.82	0.33-0.63
	82.1	3.96	0.63-1.0
	81.2	3.92	1.0-2.03
	190	9.17	2.03-4.9
	339	16.32	>4.9
Ore-storage bin	372	48.03	<0.31
	36.6	4.72	0.31-0.59
	54.4	7.02	0.59-0.95
	45.1	5.82	0.95-1.9
	89.5	11.55	1.9-4.6
	177	22.86	>4.6
Blast furnace operations, East Helena, Montana	652	41.43	<0.31
	375	23.82	0.31-0.59
	242	15.37	0.59-0.95
	132	8.38	0.95-1.9
	102	6.48	1.9-4.6
	71.1	4.52	>4.6

*Data is from Reference 6.

Particle sizes as determined by Harris and Drehmel[17] with a Brink impactor gave the data in Table 10 for ducted emissions from a lead sintering machine.

TABLE 10. PARTICLE DISTRIBUTION FOR DUCTED LEAD SINTERING MACHINES GASES*

Particle Size	Particle Loading		Size Distribution
μm	mg/m^3	gr/scf	wt%
>3.1	93.30	(0.04077)	17.75
1.8-3.1	37.12	(0.01622)	7.06
1.25-1.8	59.47	(0.02599)	11.31
0.62-1.25	135.88	(0.05938)	25.85
0.38-0.62	152.77	(0.06676)	29.06
<0.38	47.18	(0.02062)	8.97
TOTAL	525.72	(0.22974)	100.00

*Data is from Reference 17.

Some idea of the size distribution of fugitive particulates outside the boundary of a lead smelter can be gained from data by Dorn et al.[18] They measured lead, cadmium, zinc, and copper levels in suspended particulate over winter, spring, and summer seasons at a site approximately 800 meters north of a lead smelter. An eight-stage Andersen impactor sampler was used. While they did not present total particulate weights versus size, a rough idea of the particles in the respirable range can be gained from the elemental distributions in Table 11. Complete elemental distribution data is given in Table 12.

TABLE 11. DISTRIBUTION OF Pb, Cd, Zn, Cu IN RESPIRABLE RANGE NEAR A PRIMARY LEAD SMELTER*

Particle Size	Element and Percent			
μm	Pb	Cd	Zn	Cu
≥ 4.7	34.29	11.69	27.09	45.68
< 4.7	65.71	88.31	72.91	54.32

*Data is from Reference 18.

TABLE 12. AIRBORNE ELEMENTAL CONCENTRATIONS NEAR PRIMARY LEAD SMELTER*

Size	Elemental Concentration							
	Pb		Cd		Zn		Cu	
μm	$\mu g/m^3$	wt%	$\mu g/m^3$	wt%	$\mu g/m^3$	wt%	$\mu g/m^3$	wt%
> 11	0.1064	10.26	0.0009	3.63	0.0194	11.11	0.0042	21.65
7-11	0.0733	7.07	0.0007	2.82	0.0113	6.47	0.0018	9.28
4.7-7	0.1768	17.06	0.0013	5.24	0.0166	9.51	0.0029	14.95
3.3-4.7	0.1655	15.97	0.0014	5.65	0.0163	9.34	0.0026	13.40
2.1-3.3	0.0691	6.67	0.0011	4.44	0.0140	8.02	0.0015	7.73
1.1-2.1	0.1430	13.80	0.0064	25.81	0.0307	17.58	0.0016	8.25
0.65-1.1	0.1651	15.93	0.0071	28.62	0.0343	19.64	0.0008	4.12
0.43-0.65	0.1372	13.24	0.0059	23.79	0.0320	18.33	0.0040	20.62
	1.0361**		0.0248		0.1746		0.0194	

*Data is from Reference 18.

**Numbers in this column are taken as published. Individual values add to 1.0364, not 1.0361 as is shown.

COPPER SMELTING

Process Description of Copper Smelting

United States copper smelters vary more in their processing steps than do lead smelters. Broadly speaking, (1) part of the sulfur in the ore concentrate is burned in the roasting process, (2) the calcine produced in roasting is melted together with fluxes in a reverberatory furnace which produces a slag for discard and a copper bearing "matte," (3) the matte is transferred to converters into which air is blown and iron impurities are periodically removed as slag, and (4) blister copper from the converter is cast into anodes which are sent to an electrolytic refining plant. Some plants carry out the roasting in multihearth roasters, other plants use fluidized beds, and some feed the concentrate directly to the reverberatory furnace. Newer smelting processes are being developed--such as continuous smelting--which differ markedly from the general scheme described above. Reference 19 provides a good overview of the available and developing smelting technology. Some detailed engineering information on the United States plants, has been compiled by Pacific Environmental services, Inc.[20]

Figure 2 presents a flowsheet for a copper smelter having Fluosolids feed roasting and conventional reverberatory furnaces. A brief discussion of the processing steps as sources of fugitive emissions follows.

Concentrate from outdoor storage is fed to a Fluosolids roaster to remove part of the sulfur in the concentrate. Feed to this roaster is via conveyor belt and hopper. The roaster offgases pass through primary and secondary cyclones which remove most of the calcine and discharge it into reverberatory furnace charging bins through a sealed system. The roaster exhaust gases are then scrubbed to remove most of the remaining fine particulates and the clean exhaust gas stream joins the gas stream from the converters and reports to a sulfuric acid plant.

Fugitive particulate emissions from a Fluosolids roasting system are generated mainly by material handling. However, the other roasting process, multihearth roasting, is not as clean. Multihearth roasters tend to have leaks which result in fugitive particulate emissions.

One or more reverberatory furnaces follow the roasters. Calcine from the roasting step is fed to the reverberatory furnace from calcine bins through sealed feeders which feed the furnace for approximately two out of every fifteen minutes. The reverberatory furnace is typically fired with natural gas, but fuel oil can be used. Slag and matte are tapped from the reverb furnace into ladles. The reverb slag is transported to a slag dump where it is poured to resolidify. The copper-containing reverb matte is transferred to the converters for additional processing.

Furnace leakage, slag and matte tapping, and hot materials transfer are the main sources of fugitive emissions around the reverberatory furnace. Fugitive particulate emissions from this area are relatively small; very little visible fugitive emissions can be seen in this area, even during the tapping operation.[21]

Matte from the reverberatory furnace is transferred by overhead crane and charged to one of several converters. Air is blown through tuyeres into the charge, flux is added, and the slag produced is skimmed into ladles. The slag is then transferred by slag hauler to cooling pits. Water sprays in the pits (similar to lawn sprinklers) are used to assist cooling the hot converter slag which is finally broken by a bulldozer equipped with breaker bars. The broken

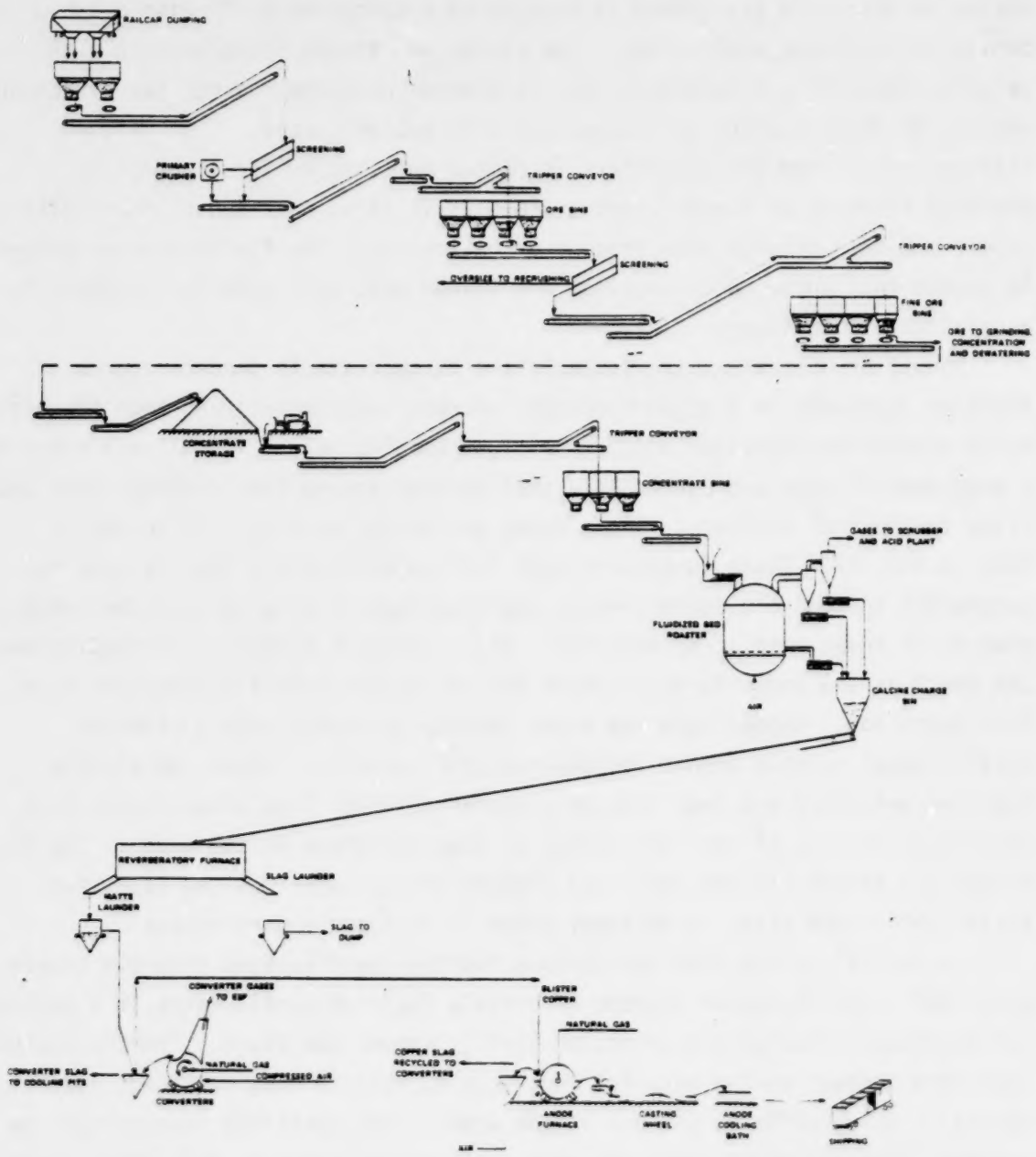


Figure 2. Flowsheet of Typical Copper Smelting Operations.

slag is returned to the concentrator where it is reprocessed with raw ore. Offgases from the converter are collected by hoods and pass through a gas cooler in which the gas stream is treated by a concurrently flowing ultrasonically dispersed water spray. The cooled gas stream flows through high velocity ducts to a scrubbing tower, is blended with the roaster gas stream and reports to an acid plant for conversion into sulfuric acid. The finished blister copper from the converters is poured into ladles for transfer by overhead crane to an anode furnace, where it is first oxidized by the addition of air and then reduced with propane or natural gas. The finished anode copper is poured into anode molds, cooled, and loaded onto rail cars for shipment to an electrolytic refinery.

Converter operations are probably the largest single process source of fugitive emissions in a copper smelter. Access requirements and high temperatures around the converter mouth make tight hooding very difficult and there is a good deal of fume and particulate that escapes around the converter hood and rises to the roof monitors. These gases are on the order of 350 to 500 °C (600 to 930 °F). There is an area near the converter aisle that is used to accumulate and recycle copper scrap; fugitive dust is generated as the crane clam shell moves this scrap material. While there is typically no hooding over the mouth of the anode furnace, there are no visible fugitive emissions from this operation. Copper from the anode furnace is tapped into a circular casting wheel to make anodes for electrolytic refining. Again, no visible fugitive emissions are seen from this operation other than steam coming from water that is used to cool the anodes as they circulate on the wheel. The hot anodes are picked off the wheel and dropped into a water cooling bath, and again, while some steam is emitted, there is no visible particulate.

In general, aside from the copious fugitive particulates from the copper converters, the strongest sources of visible fugitive particulates in a smelter are materials transfer and vehicular traffic around the plant. Traffic includes front-end loaders moving material for recycle, recycle slag handling, and general truck traffic in and out of the area. Some localized sources such as conveyor transfer points also generate fugitive particulates on a small scale.

Fugitive Emission Rate Data for Copper Smelting

The sample fugitive emissions inventory prepared by PEDCo[3] was used as the basis for estimating fugitive emissions from a copper smelter producing 100,000 metric tons per year of crude copper. The following adjustments in the PEDCo table were made to obtain the emission rates shown in Table 3: (a) roaster charging, a fairly large source was omitted because of its declining use and the small amount of fugitive emissions from the alternatives--greenfeed reverberatory charging and Fluosolids roasting; (b) an additional 40 percent was added to the process fugitive emissions to account for resuspended particulates, the 40 percent being the same relative amount of total particulate as was used for lead smelting in Table 2.

No sampling of fugitive emissions in copper smelters has been done which compares in scope to the MRI sampling[6] of lead smelter fugitive emissions. EPA is currently doing some sampling of copper smelter fugitive emissions through a contract to TRW, Inc.[22] Several operations are being sampled for fugitive emissions with the main emphasis being on fugitive arsenic emissions. However, total particulate levels are being measured on some of the samples.

Fugitive Emission Size and Composition Data for Copper Smelting

The composition data used to obtain the elemental lead emission rates in Table 3 are discussed below. The lead content of fugitive particulate emissions from copper smelting is much lower than the lead content of fugitive emissions from lead smelting. The elemental lead emission rate is far lower for copper smelting. However, other trace metals such as arsenic may be concentrated in some fugitive streams from the copper smelter. Information on the concentration of metals other than lead are presented, where available, but estimates of overall rates for elements besides lead were not made.

Fugitive emissions from material handling of copper concentrate will have metal contents similar to the concentrate itself. There is substantial variation in metals content depending on concentrate source. In particular, lead varies from around 50 ppm to over 10 percent. Table 13 shows the minimum, maximum, and production-weighted mean values for U.S. copper concentrates.[23] The production-weighted mean lead content of 1.67 weight percent was used in the fugitive emissions inventory in Table 3. Fugitive emissions from concentrate storage and handling are the largest single source of elemental lead in the

inventory. It is recognized that lead contents vary widely between smelters and lead emissions may be orders of magnitude lower for some smelters.

TABLE 13. COMPOSITION OF COPPER CONCENTRATES PROCESSED IN THE U.S.

Metal	Composition, Weight Percent		
	Minimum	Maximum	Mean as weighted by 1971 production
Cu	13.8	36.1	26.9
Pb	0.005	13.2	1.67
S	22.8	44.8	32.0
As	0.0007	12.6	0.97
Sb	0.0002	3.26	0.10
Bi	0.005	0.83	0.024
Zn	0.02	12.2	1.49
Sn	0.0003	0.1	0.0044
Ni	0.0005	2.4	0.024
Se	0.0005	0.095	0.0079

For other areas in the copper smelter, perhaps the best indication of the relative concentrations comes from some NIOSH sampling results. Between 1965 and 1973 NIOSH collected data throughout the copper industry on trace metal levels in smelters.[24] Samples from many smelters were obtained and used to get long term, industry-wide averages of exposure for the following smelter areas: (a) reverberatory furnace charging deck; (b) reverberatory furnace operators deck; (c) converters; and (d) anode casting. Both personnel and area samples were collected. Membrane filters with a 0.8 micron size were used to collect metal fumes and dusts which were then analyzed by atomic absorption. Unfortunately, total particulate levels are not given for the various areas, only ambient elemental concentrations. Table 14 summarizes the NIOSH data.

Some composition data for ducted particulate from the Bor, Yugoslavia copper smelter is given in Table 15. The lead contents for the particulate streams in the U.S. probably averages higher than those for Bor because of the

TABLE 14. ELEMENTAL CONCENTRATIONS IN AIR BY COPPER SMELTER AREA, INDUSTRY-WIDE AVERAGES*

Area	Area Sampling, mg/m^3						Personnel sampling, mg/m^3					
	Pb	Zn	Cu	As	Cd	Mo	Pb	Zn	Cu	As	Cd	Mo
Reverberatory furnace charging deck	0.07	0.07	1.1	0.04	0.005	0.014	0.07	0.12	3.4	ND**	0.005	0.003
Reverberatory furnace operators deck	0.06	0.12	2.3	0.02	0.012	0.015	0.07	0.07	1.3	ND	0.006	0.03
Converter aisle	0.05	0.05	0.22	0.01	0.003	0.004	0.03	0.04	0.11	ND	0.004	ND
Anode casting	0.01	<0.01	0.13	<0.01	0.001	ND	0.01	0.01	0.07	ND	<0.001	ND

**ND = No Data

*Data from Reference 24

TABLE 15. COMPOSITION OF DUCTED COPPER CONVERTER DUSTS FROM BOR, YUGOSLAVIA[25]

Element	Composition, Weight Percent				
	Typical concentrate	Matte	Converter dust from slag blowing	Converter dust from copper blowing	Reverberatory furnace
Cu	16	38.50	42.0	58.26	13
Pb	0.1	0.2785	0.5914	0.8984	0.5
Fe	32	32.04	12.05	5.26	17
S	42	25.80	11.82	14.01	ND*
Mo	0.005	0.0044	0.0130	0.0055	0.02
Se	0.003	0.0275	0.0325	0.0334	0.003
As	0.5	0.1907	1.1173	1.0783	2.0

*No Data

higher average concentrate lead content in the U.S.--1.67 versus 0.5 percent. To convert the NIOSH data into particulate composition, the copper content of the particulate from each sample would be needed. As this is not provided, it is instead assumed, based on the Bor data, that typical copper contents are 40 percent in particulate from the converter and anode areas and 15 percent in particulate from the reverberatory area. This was done and gave the estimated compositions in Table 16. Based on Table 16, the following lead contents were used to prepare Table 3: for charging and tapping of the reverberatory furnace, 1.5 weight percent lead; for converter charging and leakage, 2.0 weight percent lead; and for charging blister copper and anode furnace tapping and casting, 1.0 weight percent lead.

Little size data is available for fugitive particulate emissions from copper smelters. In an attempt to distinguish between "respirable" and "non-respirable" metal concentrations, the NIOSH workers took some samples through a cyclone before analyzing for metals collected on the filter; the range for respirable particle size is not given. Table 17 shows the results for 23 data points for converter furnace and crane aisle employees. Harris and Drehmel[17] provided the values in Table 18 for ducted particulates from a copper converter as sampled by a Brink, Model B, five-stage impactor.

Thompson and Nichols[26] measured ducted particulates from two copper reverberatory furnaces with cascade inertial impactors and five-stage cyclones. Data estimated from two figures they provided are given in Table 19.

TABLE 16: ESTIMATED COMPOSITION OF FUGITIVE PARTICULATES BY COPPPER SMELTER AREA[a]

Area	Area Sampling						Personnel Sampling					
	Pb	Zn	Cu	As	Cd	Mo	Pb	Zn	Cu	As	Cd	Mo
Reverberatory furnace charging deck	2.5	2.5	40[b]	1.4	0.18	0.51	0.82	1.4	40[b]	ND**	0.06	0.04
Reverberatory furnace operators deck	1.0	2.1	40[b]	0.35	0.21	0.26	2.2	2.2	40[b]	ND	0.18	0.92
Converter aisle	3.4	3.4	15[b]	0.68	0.20	0.27	1.4	1.8	15[b]	ND	0.18	ND
Anode casting	1.2	<1.2	15[b]	<1.2	<0.12	ND	0.71	0.71	15[b]	ND	<0.07	ND

**ND = No Data

[a]Elemental concentration data from Reference 24 converted to weight percent by assuming forty percent copper in particulates from reverberatory furnace areas and fifteen percent copper in particulates from the converter and anode casting areas.

[b]Assumed

TABLE 17. PERCENT OF METAL AEROSOLS IN RESPIRABLE[a] RANGE: CONVERTER, FURNACE AND CRANE AISLE EMPLOYEES IN U.S. COPPER SMELTERS

Metal	Pb	Zn	Cu	As	Cd
Average %[c] Respirable[b]	52.1	59.5	6.1	75.2	49.5

[a]No size given for "respirable." Larger aerosols were removed using a miniature cyclone before collecting remainder on a filter.

[b]Data adapted from Reference 24.

[c]23 data points each, except As only has 14.

TABLE 18. PARTICLE DISTRIBUTION FOR DUCTED COPPER CONVERTER GASES

Particle Size μm	Test 1 mg/m^3	Test 1 gr/scf	Test 1 wt%	Test 2 mg/m^3	Test 2 gr/scf	Test 2 wt%
>3.1	3.52	(0.00154)	1.08	10.23	(0.00447)	3.84
1.8 - 3.1	13.59	(0.00594)	4.18	15.10	(0.00660)	5.68
1.25 - 1.8	57.02	(0.02492)	17.54	56.09	(0.02451)	21.08
0.62 - 1.25	222.04	(0.09703)	68.30	137.03	(0.05988)	51.49
0.38 - 0.62	16.36	(0.00715)	5.03	42.95	(0.01877)	16.14
<0.38	12.58	(0.00550)	3.87	4.71	(0.00206)	1.77
TOTAL	325.11	(0.14208)	100.00	266.11	(0.11629)	100.00

TABLE 19. PARTICLE DISTRIBUTION FOR DUCTED COPPER REVERBERATORY FURNACE GASES[26]

Particle Size μm	PLANT A mg/acm	PLANT A wt%	PLANT B mg/acm	PLANT B wt%
> 4	10	7	80	28
2-4	20	14	50	17
1-2	31	22	40	14
0.6-1	27	20	38	13
0.3.0.6	24	17	65	22
<0.3	28	20	17	6

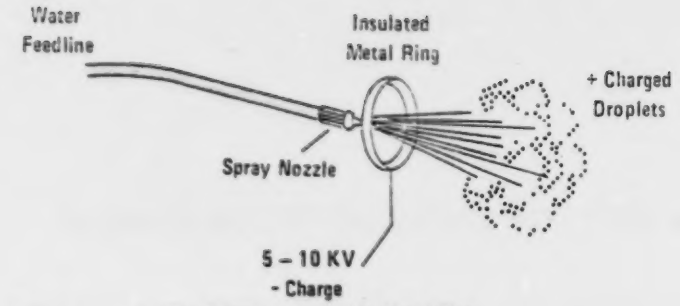
4.0 CHARGED FOG SPRAYS FOR CONTROLLING FUGITIVE EMISSIONS

This section describes charged fog spray devices, discusses theoretical and experimental efficiencies for sprays, and presents the efficiency and costs used as the basis for evaluating charged fog sprays.

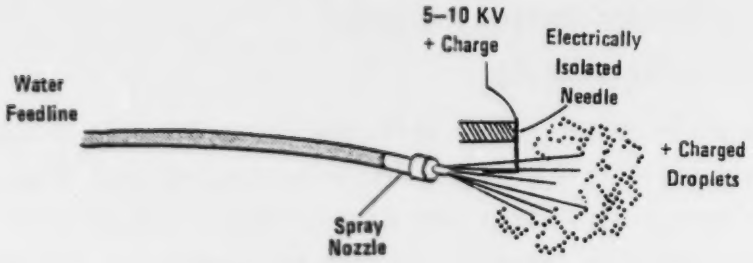
DESCRIPTION OF CHARGED FOG SPRAY DEVICE

The spray of fine water droplets is a well-known means of dust removal. The various types of scrubbers rely on water droplets to sweep dust from the inlet gases, and water sprays have often been used in mining and material handling to reduce dust levels in the air. Charged fog sprays, as evaluated in this report, differ from conventional water sprays in that the droplets carry a charge of static electricity. Also, the droplets used for an electrostatic spray may be of a finer size. Since most fine particulates carry a natural electrical charge,[28] particle collection can be improved via electrostatic attraction if the water spray droplets are charged to the opposite polarity. The charged water droplets then exert attractive forces on the oppositely charged particles and each droplet collects more particles as it travels through the dust-laden gas.

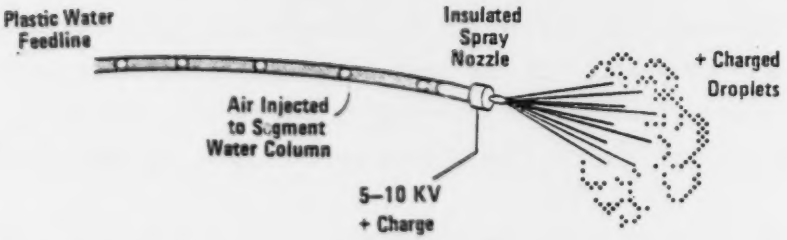
The water droplets in a spray may be electrostatically charged by several methods. Droplets may be charged via induction from a metal ring surrounding the spray (Figure 3a), via a charged needle in the spray (Figure 3b), or by direct electrical contact with the water (Figure 3c). In the third case, the spray nozzle must be insulated in such a way as to prevent current leakage through the support structure or the water feedline. Hoenig[28] mentions isolating up to 20kV by injecting air into a plastic tubing feedline. The injected air breaks the continuous water column into segments and prevents electrical leakage via conduction through the water column. Hassler[29] has reported an autogenous charging method which does not require any voltage source. Droplet charges result from water-to-metal friction in a grounded spray nozzle (Figure 3d). While not requiring any voltage source, the method does require very pure, deionized water. Autogenous charging will work only if the nozzle



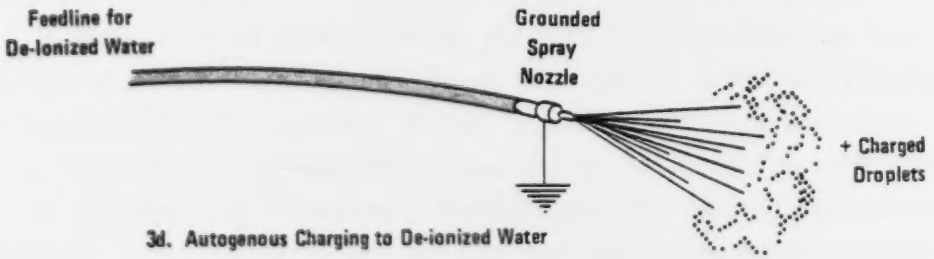
3a. Charge Induced Via Metal Ring.



3b. Charging Via Needle.



3c. Direct Contact Water Charging.



3d. Autogenous Charging to De-ionized Water

Figure 3. Means of Producing a Charged Water Spray.

is grounded and the water acts as an insulator; even tap water has too many impurities to produce a charged spray by this means.

The only known commercial version of an charged fog spray device is the Electrostatic Fogger I® manufactured by Ransburg Electrostatic Equipment,* a division of Ransburg Corporation, Indianapolis, Indiana. The original work on the charged fog sprays was done by Dr. Stuart Hoenig at the University of Arizona under support provided by the American Foundry Society. Dr. Hoenig approached Ransburg and discussed the possibility of Ransburg manufacturing the Electrostatic Fogger. Ransburg as a company has filed application for a patent on the electrostatic fogging principle, and this patent is now pending. Ransburg has recently begun to commercially market the Electrostatic Fogger I. Their prior experience has been with electrostatic paint-spraying equipment.

The following information was obtained during discussions with Ransburg.[30]

The device functions by applying a 5 to 10 kilovolt induced voltage on a metal ring surrounding the spray nozzle. This changing technique is the subject of a U.S. Patent*. The droplets coming out the nozzle charge either positively or negatively as controlled by connections in the control box. The Fogger does not permit variation of the voltage applied to the metal ring other than polarity. The control box for the Fogger is mounted separately from the spray nozzle itself. It contains a 40 micron filter on the water supply and a pressure regulator to maintain constant water supply pressure to the nozzle. Likewise on the air supply to the box there is a 10 micron filter and a pressure regulator. The box contains an indicator light which will dim when the voltage to the spray nozzle is not high enough for one reason or another. It also has a light which indicates when the unit itself has power. Each spray has its own control box, although Ransburg can arrange to put multiple boxes inside one larger cabinet. They like the approach of individual control boxes from the standpoint that the entire water spray network is not dependent on any single component. Electrical requirments are 30W of 115V, 60Hz.

Ransburg said the droplet size from the Fogger I is typically 25 to 75 microns, but did not provide any further data on the droplet size distribution.

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*During report preparation (12/78), it was found that Ransburg had sold all market rights, patents, and manufacturing equipment for the Electrostatic Fogger to Ritten Corporation Ltd., 40 Rittenhouse Place, Ardmore, Pa.

The spray device itself is a fairly simple looking item consisting of a nozzle surrounded by the metal ring with a plastic case about the device. Air provided to the nozzle is used mostly to atomize the water with a small amount injected tangentially into the ring around the spray to produce a coanda effect (that is, a swirling airflow around the spray) and project the water droplets farther than would otherwise be obtained. Air requirements are up to 13 SCFM at 110 psig. The Fogger I provides a water stream which is indeed a "fog" and not a mist or a spray. Typically the water droplets evaporate 2.5-3 meters (4-6 feet) from the spray nozzle and the width of the spray is about 0.7 meters, (2 feet).

The particular Fogger I which is now being marketed by Ransburg is not approved for use in hazardous atmospheres. However, Ransburg has some patented technology in the way of safety equipment which can be used to make these high voltage devices sparkproof. The company has manufactured paint sprayers approved for NFPA Class 1, Division D uses (applications with hydrocarbon solvents used in spray painting). This feature is provided by using a high resistance element in the charging circuit which limits the steady state current flow and by keeping the mass (and thus the capacitance) downstream of this resistor very small.

Ransburg is currently developing a second electrostatic fog spray to be called Fogger II, which will be of much larger capacity. Fogger I is rated for 16cm^3s (0.25 gpm) of water. The Fogger II is being designed for up to 190 cm^3s (3 gpm) of applied water and up to 10 meters (30 feet) spray distance. The larger flow version of the Fogger will not have as small a droplet distribution as the Fogger I. The water droplets in it are also charged with a metallic ring surrounding the spray nozzle, but the Fogger II will use hydraulic atomization as opposed to air atomization used in the Fogger I. With the much higher spray rates in the Fogger II, air usage would be excessive using air atomization in some applications. However, it will permit an air source to produce the coanda effect if needed to project the spray farther. In the Fogger II, the control box will include an integral pump to provide the high pressures of 500 psi required for hydraulic atomization of the water spray.

COLLECTION EFFICIENCY OF CHARGED FOG SPRAYS

Two areas important in evaluating sprays are collection efficiency and droplet evaporation; several studies have been made in both areas. Some of the more advanced treatments of single droplet collection of dusts have been in the field of meteorology concerning the scavenging of airborne dusts by rain drops.[31-35] Droplet evaporation has been treated by researchers in combustion[36,37] and spray drying.[38,39] (Spray drying is the production of dry powder by spraying a solution into warm gas.) Masters[39] discusses not only droplet evaporation, but also types of spray nozzles, droplet trajectories, and the effect of suspended or dissolved solids in the spray. An overview of the theory of charged droplet collections follows; for a more detailed discussion, see the reports by Melcher and Sachar.[40,41]

For a single water droplet and a single dust particle, there are several forces acting simultaneously that affect the likelihood of particle capture. Fairly good theories exist which can predict how the various forces affect the efficiency of dust collection for well-controlled experimental conditions. In a practical application, the theories are less useful; operating conditions vary, and it is very hard to choose representative values for many of the parameters in the theories--dust composition, loading, size, and charge; spray size and charge; ambient temperature and humidity; etc.

This work approaches the problem of applying theory to practical cases by (a) briefly discussing the different collection mechanisms and their relative magnitudes, (b) presenting some theoretical predictions of the effect of electrostatic charge on collection efficiency, and (c) showing how droplet evaporation and water application rate should affect efficiency of dust removal. Thus, the emphasis is on using the theory to get directional trends rather than absolute values.

Impaction/Interception

These collection mechanisms are closely related and are the dominant forces in collecting larger particles with water sprays. When a droplet and a particle approach each other on a collision path, the particle tends to follow the fluid streamlines and be swept around the larger droplet. Because of its

inertia, however, the particle does not exactly follow the fluid path, but instead cuts across some streamlines. Depending on the initial trajectory and velocity, it may impact directly on the droplet (Figure 4a), barely graze the droplet (Figure 4b) or entirely miss the droplet (Figure 4c). The "direct-hit" collection of very small particles is termed impaction, while interception refers to the grazing trajectory of larger particles. The collision efficiency (i.e., the fraction of area swept clean of particles by a water droplet) is improved by increasing the relative velocities between droplet and particle, increasing the particle diameter, and increasing particle density.

Diffusion

Particles of submicron size, and thus low inertia, are rarely captured by impaction/interception because they follow the gas streamlines around the particles. However, some of the very small particles are captured as they move past a droplet because they diffuse to the droplet surface via the random bombardment by gas molecules. This collection mechanism is termed diffusion and is improved with decreasing particle size. For particles one micron or larger, this mechanism is negligible.

Phoresis

Phoresis is the process in which particles move because they are subjected to a gradient in temperature (thermophoresis) or vapor pressure (diffusiophoresis). If a liquid is evaporating at one surface and being absorbed at another parallel surface (Figure 5a) and there is no temperature gradient, the particles will experience a net force in the direction of vapor molecule movement. Similarly, if one parallel plate is kept hotter than the other, the more frequent gas collisions on the hotter side of the particle will force the particle toward the cooler plate (Figure 5b).

Phoretic forces are not very strong compared to the other collection forces for particles larger than two or three microns. For the particular case of submicron particles around an evaporating water droplet, phoretic effects become significant. However, their net effect depends on the ambient humidity, the droplet temperature, and the ambient temperature, and many researchers neglect one or both of these forces.

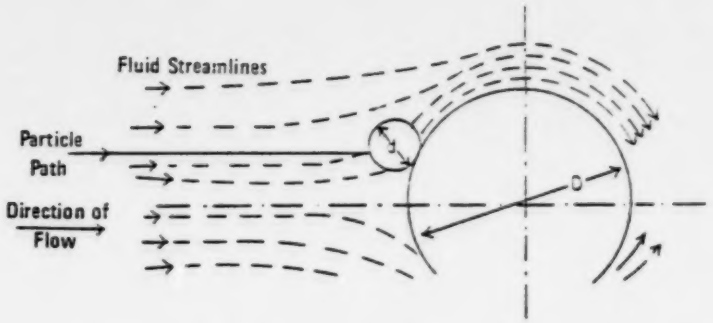


Figure 4a. Path for Direct Impaction of Particle.

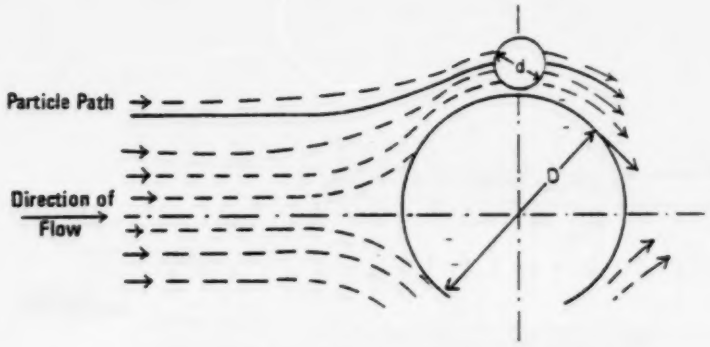


Figure 4b. Path for Limit of Interception of Particle.

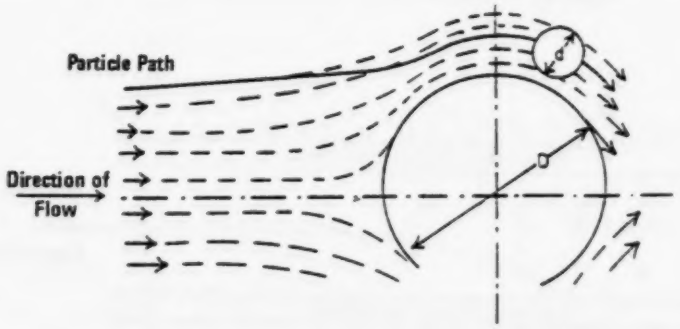


Figure 4c. Path for Particle Not Collected by Droplet.

Figure 4. Particle Trajectories Around a Water Droplet.

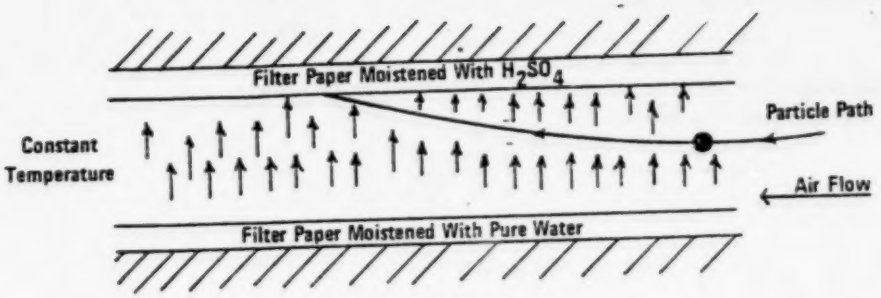
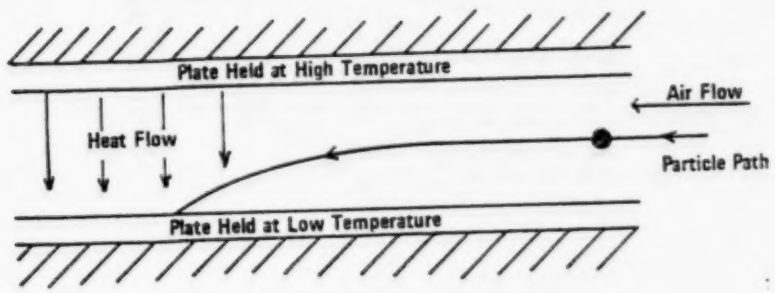


Figure 5a. Diffusiophoresis in Isothermal System.



5b. Thermophoresis Due to Temperature Gradient.

Figure 5. Thermophoretic and Diffusiophoretic Forces.

Electrostatic Attraction

Practically all aerosols carry an electrical charge. The presence of charge on the particle or the droplet (or both) affects the particle trajectory around the droplet and can improve (opposite charges) or reduce (alike charges) the collection efficiency. The interacting forces increase as charges increase.

The maximum charge a droplet can carry (termed the Rayleigh limit) is reached when the mutual repulsion of the charges accumulated on its surface equals the surface tension holding the droplet together. The Rayleigh limit is typically reached for evaporating droplets. At the Rayleigh limit, evaporating droplets eject smaller charge-carrying droplets to dispose of excess charges.[41] The Rayleigh limit on water droplet charging is shown in Figure 6--for 100 m diameter droplets, this limit is about $5X10^{7}$e per droplet ($8x10^{-12}$ coulomb).

For a solid particle, the maximum charge is limited by the point where ions or electrons are spontaneously emitted from the surface. However, this limit is rarely approached. Several workers have reported the average charge of all the particles in a dust sample to be 5 to 20 electron units (e) positive per particle ($8x10^{-19}$ coulombs).[29,42,44] Not all particles are positively charged, however. There is a distribution of both positively and negatively charged particles within the dust sample as is schematically shown in Figure 7.

Thus far, four collection mechanisms--impaction/interception, diffusion, phoresis, and electrostatic attraction--have been highlighted. The expected electrical charges on droplets and particles has also been discussed. How can this information be applied to the case of interest--reduction of large scale emissions of fugitive particulates from smelters? In an industrial application, the water spray droplets are charged and projected into the dusty gas stream. As the water droplets travel through the particulate cloud, they capture dust particles, and finally, the droplets settle out of the gas stream. Small particles which would otherwise remain suspended will settle out because they have either become attached to the larger water droplets or agglomerated with other particles. Grover et al.[35] determined the collision efficiency of a droplet/particle pair for the case of water droplets falling at their terminal velocity. They calculated several cases while varying droplet size, humidity,

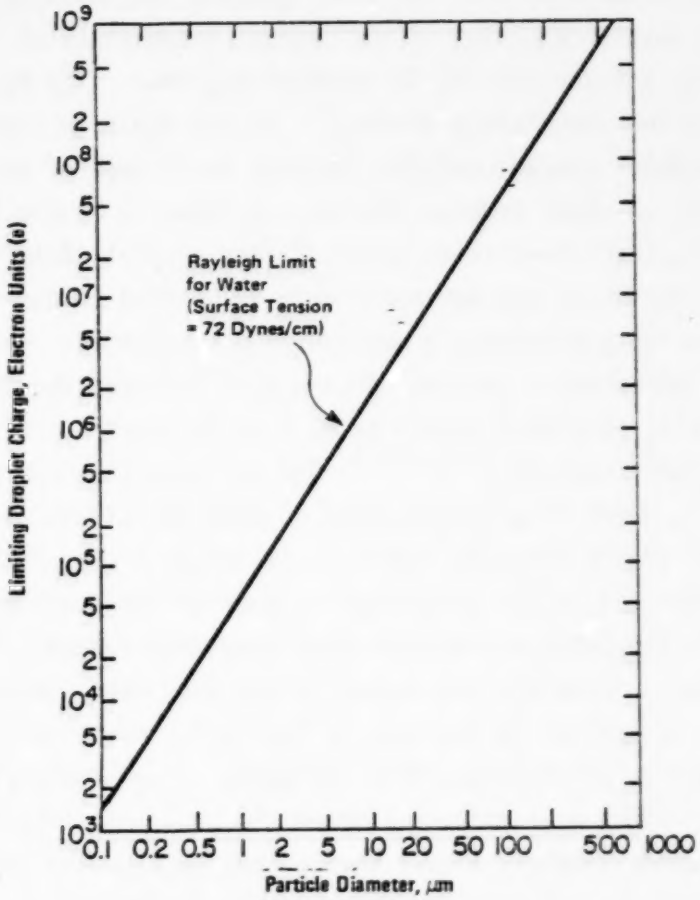


Figure 6. Limiting Charge for Water Droplets.

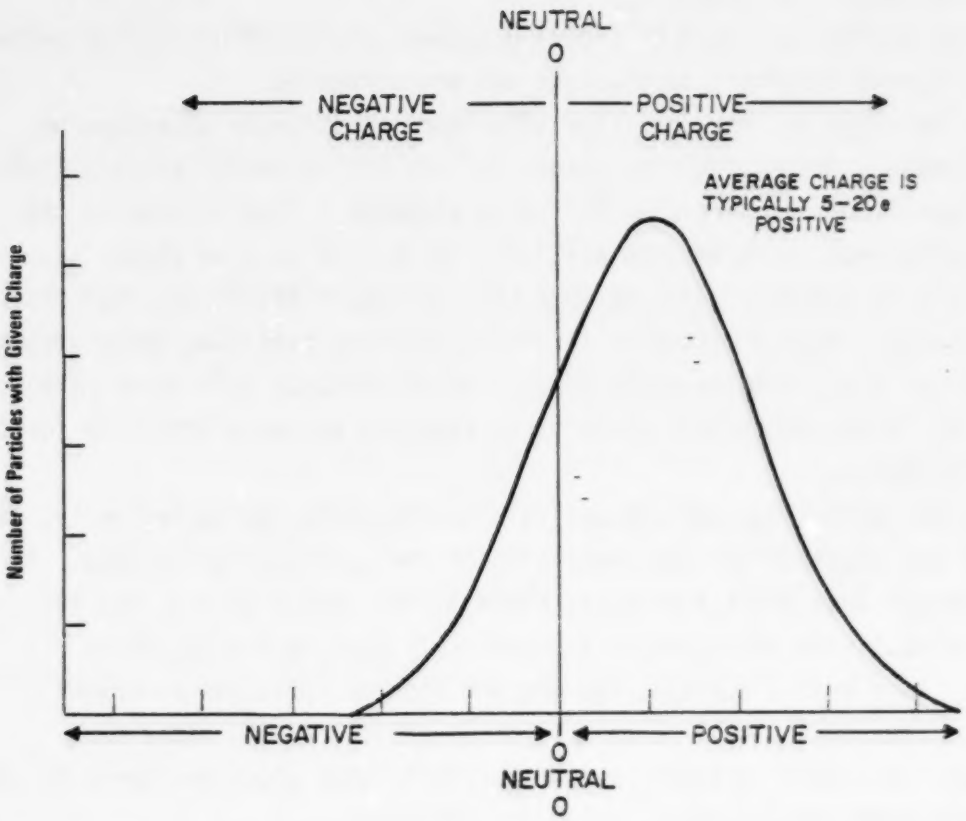


Figure 7. Typical Charge Distribution for Micron Size Particles.

electric charge, etc. Cross-plots showing the effects of several variables are seen in Figure 8. This data can ultimately be used to calculate overall collection efficiency of a spray.

At first glance, the data in Figure 8 appears overwhelming, but on closer inspection several important conclusions can be abstracted.

Figure 8a shows how the collision efficiency is strongly dependent on particle diameter, decreasing from nearly 1.0 for 100 μm particles to a minimum value of about 0.001 for particles 2-3 μm in diameter. This minimum in the collision efficiency curve implies particles in the 2-3 μm size range, as are commonly found in smelters, will be much more difficult to collect than the larger particles. Notice also that for any given size particle, water droplet size influences the collision efficiency. Larger droplets tend to be more effective for larger particles, while finer droplets are more effective for the submicron particles.

Figure 8b depicts how the ambient relative humidity (or equivalently, the tendency of the droplets to evaporate) affects the collision efficiency. For particles larger than about 3 microns, humidity has little effect, but for finer particles, drier environments theoretically improve the collision efficiency. In a real situation, the shorter droplet lifetimes at higher evaporation rates might override the collision efficiency improvements.

The most pertinent information in Figure 8 is that shown in Figure 8c--the effect of electrostatic charge on collision efficiency.

First, some background on the assumptions used to calculate Figure 8c. Grover and coworkers[35] solved the problem in which the droplet and the particle have equal, but opposite, charges. The total charge on a droplet (or particle) was assumed to increase proportionately with surface area. They calculated three cases: (a) no static charges present; (b) Q droplet = $+0.2a^2$, Q particle = $2.0r^2$ (where Q is charge expressed in esu, a is the drop radius in centimeters and r is the particle radius in centimeters); and (c) Q droplet = $+2.0a^2$, Q particle = $0.2r^2$. A fourth efficiency curve is shown which was calculated by a less rigorous method[45] to give a rough idea of the curve for Q droplet = $20a^2$ and Q particle = $20r^2$. For particle sizes typical in smelting

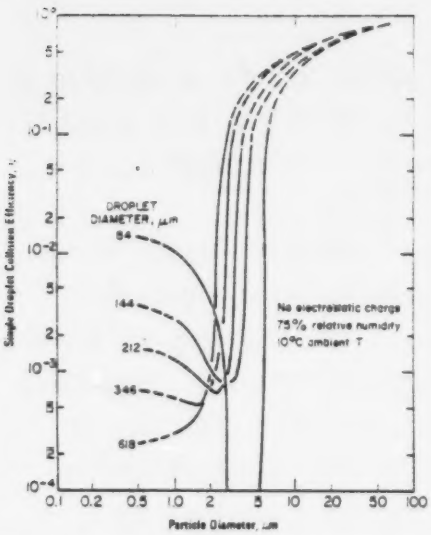


Figure 8a. Effect of Droplet Diameter on Collision Efficiency.

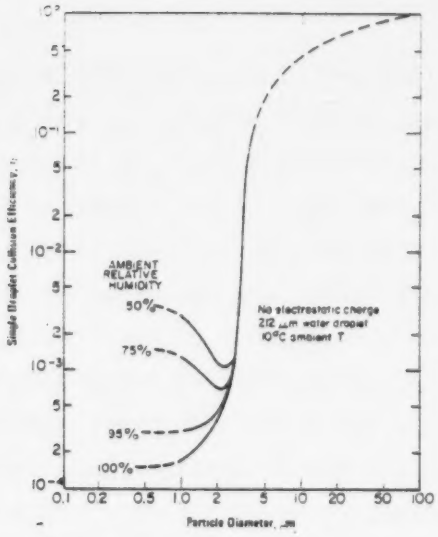


Figure 8b. Effect of Relative Humidity on Collision Efficiency.

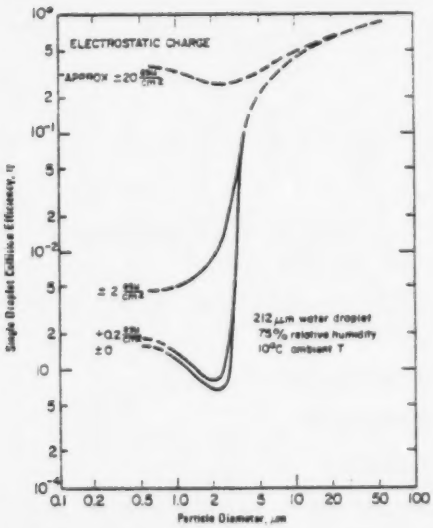


Figure 8c. Effect of Electrostatic Charge on Collision Efficiency.

Figure 8. Effects of Particle Size, Droplet Size, Relative Humidity, and Electrostatic Charge on Collision Efficiency.

applications (3 micron particles and 200 micron droplets) and for a particle of average excess charge (10e) and a water droplet at its Rayleigh limit ($2x10^8e$), it is estimated that the collision efficiency curve will lie between the $Q = 2.0r^2$ and the $Q = 20r^2$ curves in Figure 8c.

Disregarding the details of the assumptions made, and the variations due to size, there are two broad conclusions that are apparent from Figure 8c. First, the presence of electrostatic charges increases the collision efficiency for all size particles and eliminates the minimum around 2 microns. Secondly, charged sprays in industrial applications would have collision efficiencies roughly 5-10 times higher than uncharged sprays. Caution: these collision efficiencies are for single droplets only, they do <u>not</u> indicate that the overall collection of dusts by a spray will be 5-10 times higher. The relationship between single droplet collision efficiency and overall collection efficiency is presented next.

A relationship is needed between the collision efficiency and the other important variables such as flow rate, spray rate, system geometry, etc. In a paper on suppressing airborne coal dust, Cheng[46] presents such a relationship for overall efficiency of a water spray on a dust cloud:

$$E_o = 1 - \exp\left[\frac{-3\eta}{2D} \cdot \frac{Qw}{Qg} \cdot L\right] \qquad (1)$$

where E_o = overall number of dust particles collected by the spray

= single droplet collision efficiency as discussed above

D = droplet diameter

Qw = water flowrate

Qg = gas flowrate

L = a characteristic length which measures the length of the spray trajectory through the gas.

Equation 1 is obviously only an idealized version of the complex interaction between a spray and a moving dust cloud, but the form of the equation is instructive. By rearranging, it is seen that log $1/(1-E_o)$ is directly proportional to η and to Q water, and inversely proportional to Q gas if the droplet size and spray geometry are constant. These relationships together with Figure 8 can be used to predict charged spray efficiencies from experimental results for uncharged commercial sprays.

BASIS OF COLLECTION EFFICIENCY FOR COMMERCIAL DEVICES

Much of the experimental measurement of fine particulate removal by water sprays has been done by researchers attempting to reduce the level of respirable dusts in underground coal mines.[47] Uncharged sprays reportedly reduce respirable dust 20 to 60 percent with 30 percent seeming to be an average value.[48] Extrapolating 30 percent efficiency assuming equivalent geometry, water rate, and droplet sizes, a charged fog spray with a five times higher single droplet collision efficiency would remove about 80 percent of the respirable dust. Practically, the charged fog efficiency would not be as high because of much lower water application rates for charged fog sprays compared to conventional sprays.

Lab scale experiments and limited commercial applications of charged fog sprays as cited by Hoenig[28] mostly range between 50 to 80 percent collection efficiency. This agrees well with the above analysis.

There is an important limitation on the charged fog spray applications cited so far--they have been in enclosed areas or on applications in moderately still air. Spray performance would not be anticipated to be very good for highly turbulent air streams as are often encountered in smelting. The reasoning follows.

The critical parameter in spray performance is the ratio of the spray rate to the volume of gas treated. For still air or confined spaces, the water droplets settle through the gas and collect and agglomerate particles. All together, the water from one small spray may be distributed through 2-4 m^3 of volume (30-100 ft^3). In an open, highly turbulent situation, both the dust particles and the water droplets would be dispersed outward and become more and more diluted into larger and larger volumes of gas. The effective volume of gas that must be treated is no longer just confined to the area around the

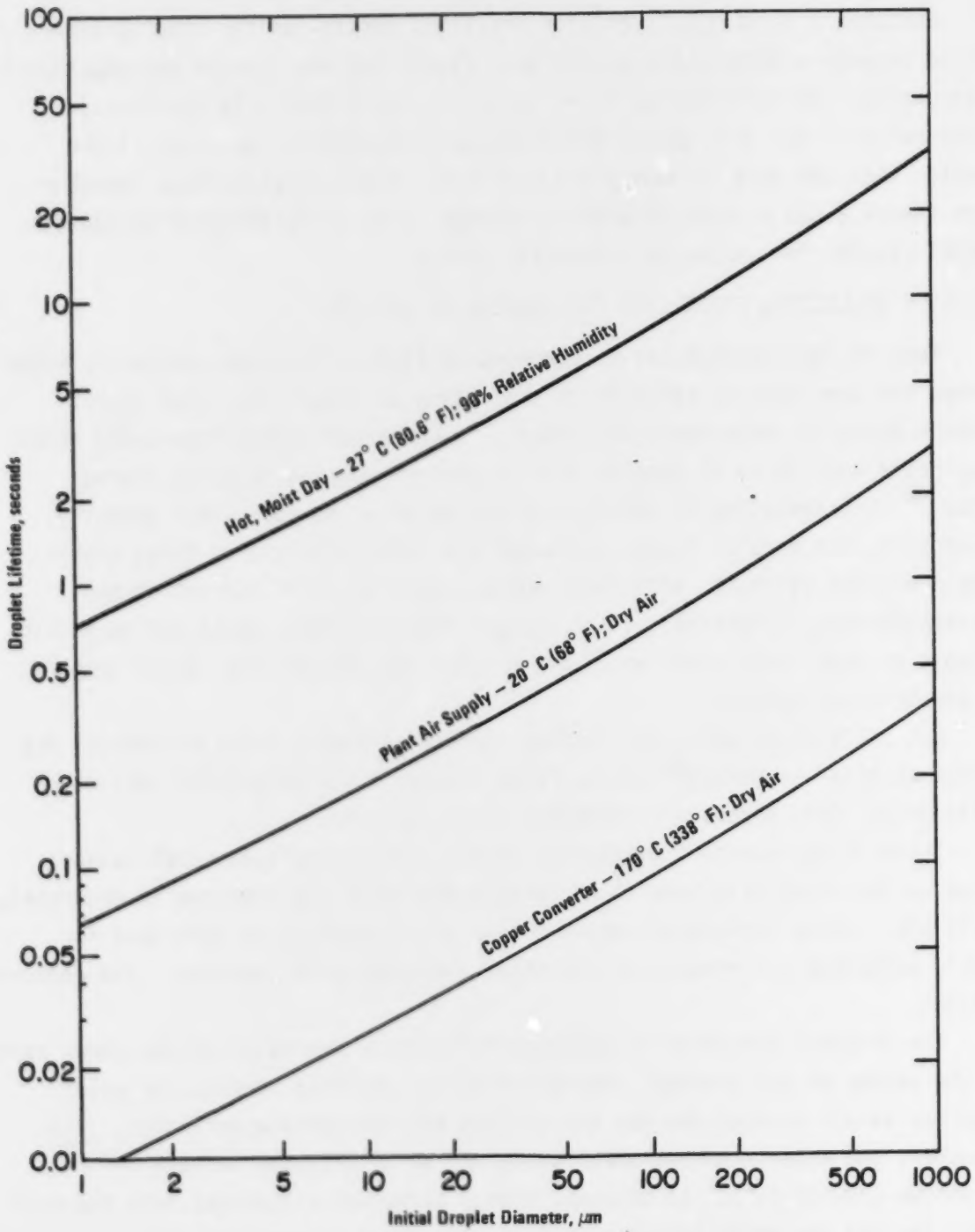


Figure 9. Lifetime of Water Droplets Traveling at Their Terminal Velocity.

spray, but also includes the entire area of turbulence which is greater by maybe a factor of 1,000 since volume goes up with the cube of distance. (That is, if instead of being dispersed three feet, turbulence disperses the particles and droplets thirty feet, the gas volume goes from 9 ft^3 to 9000 ft^3.) A second factor must also be cosidered in open, turbulent environments. When the water droplets that do collect particles eventually settle out of the air, the particulate will be spread over a large area and in a sense, not be "collected" at all.

A simplifying assumption in the above analyses has been that of no droplet evaporation. When sprayed into air, the small droplets formed by a charged fog device will evaporate unless the ambient air is saturated with water. In most cases of practical concern, the air is not saturated, and a droplet will completely evaporate after a certain period. The droplet lifetime determines the effective contact time between the spray and the dust-laden stream, and thus strongly impacts on the overall spray efficiency- a short lifetime droplet will disappear before collecting very many dust particles. Some work with charged fog sprays in high temperature enclosed systems is being done by Dr. Hoenig at the University of Arizona at Tucson, but at this time the understanding of the data is incomplete.

The temperature and humidity of the ambient air are the two main variables affecting evaporation rate. When a droplet evaporates two simultaneous processes occur--heat flows toward the droplet from the surrounding air and water vapor molecules diffuse away from the droplet surface into the surrounding air. High ambient temperature increases heat flow to the droplet and hastens evaporation, while low ambient humidity increases the rate of evaporation by speeding the diffusion of water vapor molecules away from the droplet surface.

Figure 9 depicts water droplet lifetime versus droplet diameter for three cases of practical significance: (a) 20°C (68°F), dry air which represents a plant compressed air supply; (b) 27°C (80.6°F) air with a relative humidity of 90 percent which represents a warm, moist environment; and (c) 179°C (388°F), dry air which represents the severe conditions around a copper converter or furnace taphole. Notice how, for a 200 μm droplet, the lifetime is of the order of 0.1 second for the high temperature (170°C) conditions. During such a short lifetime, the droplets can neither travel very far, nor encounter very many dust particles, and correspondingly poor dust collection would be expected under such conditions. Indeed, a 100 μm drop falling at its terminal velocity in dry 170°C air will only travel 7 cm (3 in.) before evaporating.

Summarizing the discussions of this section: (a) while for uncharged sprays, there is a minimum in the collection efficiency for about two micron diameter particles, there is not any such minimum for charged sparys and some improvement or collection of respirable dust is expected from charging; (b) the charged fog sprays are best suited to localized sources of dust, suspended in a low velocity or stationary gas stream; (c) the combination of high temperatures and excessive gas turbulance rule out charged fog sprays for areas such as copper converter leakage or furnace taphole emission control; and (d) at reasonable water application rates, the charged fog sprays are unlikely to have efficiencies approaching 90 percent--overall collection efficiencies on the order of 60 percent are more likely.

COST DATA AND UTILITY CONSUMPTION FOR CHARGED FOG SPRAYS

The total erected cost for a charged fog spray device consists of: (a) purchased equipment cost; (b) installation materials; (c) installation labor; (d) auxliary equipment costs; and (e) indirect costs. The estimates for each category are further discussed below--bases, assumptions, and cost data. Table 20 summarizes the cost calculations.

The charged fog sprays themselves are the largest component of purchased equipment cost. A small charged fog spray, having a coverage area of approximately 2 ft by 6 ft, is sold for $2,000.[30] This includes 50 ft of air hose, water hose, and shielded high voltage cable, and does not include any quantity discount which may be available for purchasing several devices. We have assumed a 25 percent discount for buying a large number of spray units, making the estimated price for one unit $1,500.

A larger scale charged fog device under development, which has a coverage area of approximately 6 ft by 20 ft has not been commercialized and no sales price is available. Often, prices are extrapolated from one capacity to another using the "0.6 power rule," but since costs for the electrical equipment and spray nozzle for a charged fog device are fairly independent of size, a smaller exponent is appropriate for the cost-capacity equation. An exponent of 0.1 is typical for conventional spray nozzles in the size range of interest.[49] An exponent of 0.2 was used to prorate the costs of the smaller device: Cost of large spray = (120 ft^2 coverage area/12 ft^2 coverage area)$^{0.2}$ x ($1,500 cost

TABLE 20. SUMMARY OF TOTAL ESTIMATED COSTS FOR CHARGED FOG SPRAY DEVICE*

Item	Cost per charged fog spray device: Small fog spray	Large fog spray (with air)	Large fog spray (no air)	Mobile fog spray
Purchased Equipment	$1,535	$ 2,454	$ 4,400	$ 2,400
Installation Materials	97	97	83	- 0
Total Materials	1,632	2,551	4,483	2,400
Installation Labor	318	318	292	75
Indirect Costs				
Construction Overhead	223	223	204	53
Engineering	228	357	628	336
Taxes and Freight	130	204	359	192
Total Indirects	581	784	1,191	581
Direct and Indirect Excluding Auxiliary Equipment	2,531	3,653	5,966	3,056
15% Contingency	380	548	895	458
Auxiliary Equipment	1,453	7,380	230	- 0 -
GRAND TOTAL	$4,364	$11,581	$ 7,091	$ 3,514

*See Tables 12-15 and text for break down of costs and bases used.

of small spray) = $2,400, quantity discount included. For the version of the larger charged fog spray which uses no atomizing air, an additional $2,000 is added to account for the cost of an integral high pressure water pump needed for hydraulic atomization. For a mobile version of the spray (no air source; D.C. battery powered) with an intermediate coverage area, a price identical to the large spray device was used to allow for additional complexity of construction.

Since industrial plant air and water systems usually contain solids that could rapidly plug the filters, built in sprays, additional cartridge filters for both the air and water supply to the sprays have been included. It is

assumed a bank of four sprays is attached to each filter. A prorata share of the cost of a cartridge filter for the water and a combination coalescer/filter for the air is charged to each spray. Costs for the systems are summarized in Table 21.

TABLE 21. ESTIMATE OF PURCHASED EQUIPMENT COSTS FOR CHARGED FOG SPRAY DEVICES*

Item	Cost per Spray Device	Basis for Calculations
Small Charged Fog Device	$1,500	Current sales price less assumed 25% discount for purchase in quantity.
Large Charged Fog Device with Air Atomization	$2,400	Cost of small fog spray prorated by coverage assuming 0.2 exponent in cost-capacity equation.
Large Charged Fog Device with Hydraulic Atomization	$4,4	Cost of large fog spray having air atomization plus $2,000 for integral high-pressure water pump.**
Mobile Charged Fog Device	$2,400	Spray for mounting on front-end loaders, etc. Assumed to have smaller coverage area than large device, but cost the same because of more complex construction.
Share of Air Coalescer		Assume four small fog sprays per 100 acfm filter of cost $75; two large fog sprays per 100 acfm filter
Small fog spray	$ 19	
Large fog spray	$ 38	
Share of 40 micron Water Filter		Assume four fog sprays per 15 gpm filter of cost $66.
Small fog spray	$ 16	
Large fog spray	$ 16	

*Only a part of total costs associated with charged fog spray device installation. See Table 20 for summary of complete costs.

**Reference 50

***Reference 51

Installation materials include any water or air piping, mounting equipment, and electrical hardware. It is assumed that the high voltage cable will be installed in 1/2 in. rigid, galvanized conduit. Fifty foot of conduit per spray is assumed. In addition, a prorata share of electrical and water tie-ins

are charged to each spray. Again, a bank of four charged fog sprays is assumed, and 50 ft of #14 copper wire with accompanying conduit, plus two water tight and dust tight mounting boxes and 50 ft of one-half inch carbon steel water line are included for each bank. Calculations for installation materials are shown in Table 22.

TABLE 22. ESTIMATE OF INSTALLATION MATERIAL COSTS FOR CHARGED FOG SPRAY DEVICE*

Item	Cost per Fog Spray Device	Basis for Calculations
Conduit for High Voltage Cable	$ 21	50 ft of 1/2" diameter rigid diameter rigid galvanized steel conduit per fog spray at $0.42/ft**
Share of Conduit for 110V Feed-line	$ 5	50 ft of conduit as above for a bank of four fog sprays.
Share of Wiring for 110V Feed-line	$ 35	50 ft of #14 copper wire for a bank of four fog sprays at $2.80/ft.**
Share of Mounting Boxes for 110V Feed-line	$ 13	Two pull-boxes, water tight and dust-tight for a bank of four fog sprays at $36 each.**
Share of Water Supply Line	$ 9	50 ft of 1/2" diameter Schedule 40, galvanized, steel pipe for a bank of four fog sprays at $0.69/ft.**
Share of Air Supply Line	$ 14	50 ft of 1" diameter, Schedule 40, galvanized, steel pipe for a bank of four fog sprays at $1.10/ft.**

*Only a part of total costs associated with charged fog spray device installation. See Table 20 for summary of complete costs.

**Reference 52.

Installation labor for electrical equipment as cited by Means[52] is used. An additional two hours per fog spray of electrician labor and two hours of laborer time per fog spray are included for mounting of the fog spray control box and the fog spray nozzle. Two hours per fogger of pipefitter time is included for water line connections. Labor costs are tabulated in Table 23.

TABLE 23. ESTIMATE OF INSTALLATION LABOR COSTS FOR CHARGED FOG SPRAY DEVICES*

Item	Cost per Charged Fog Spray Device	Basis for Calculations
Conduit for High Voltage Cable	$ 61	50 ft of 1/2" diameter rigid galvanized steel conduit per fog spray at $1.22/ft.**
Share of Conduit for 110V Feed-line	$ 15	50 ft of conduit as above for a bank of four fog sprays.
Share of Wiring for 110V Feed-line	$106	50 ft of #14 cooper wire for a bank of four fog sprays at $8.45/ft.**
Share of Mounting Boxes for 110V Feed-line	$ 14	Two pull-boxes, watertight and dust-tight for a bank of four fog sprays at $27 each.**
Share of Water Supply Line	$ 21	50 ft of 1/2" diameter Schedule 40, galvanized, steel pipe for a bank of four fog sprays at $1.68/ft.**
Share of Air Supply Line	$ 26	50 ft of 1" diameter, Schedule 40, galvanized, steel pipe for a bank of four fog sprays at $2.10/ft.**
Mounting of Spray Nozzle and Control Box	$ 75	Per fog spray: 2 hrs. of electrician at $13.70/hr.; 2 hrs. of pipefitter at $14.00/hr.; and 2 hrs. of laborer at $9.70/hr.**

*Only part of total costs associated with charged fog spray device installation. See Table 20 for summary of complete costs.

**Reference 52

Some investment is associated with auxiliary equipment needed for the fog sprays. A prorata share of a plant air compressor (based on air consumption) is charged to each fog spray. A 10,000 standard cubic feet per minute centrifugal compressor is used for the basis. Similarly, a share based on water consumption of a 1,000 gpm centrifugal pump station, discharging at 100 psig, is charged to each spray. Costs for these auxiliary pieces of equipment are presented in Table 24. Notice that the share of air compressor costs is a large share of the costs for air atomized systems.

TABLE 24. ESTIMATE OF AUXILIARY EQUIPMENT COSTS FOR CHARGED FOG SPRAY DEVICE

Item	Cost per Charged Fog Spray Device	Basis for Calculations
Share of Compressor Costs for Plant Air System		Proration by air consumption of the investment for a 10,000 scfm centrifugal compressor delivering air at 100 psig. (Estimated total erected cost = $1.43 x 10^6) Small fog spray air consumption of 10 scfm. Large fog spray air consumption of 50 scfm for air atomized version, no air for hydraulically atomized version. No air consumption for mobile fog spray.
Small fog spray	$1,430	
Large fog spray (air atomized)	$7,150	
Large fog spray (hydraulically atomized)	-0-	
Mobile fog spray	-0-	
Share of Pump Costs for Plant Water System		Proration by water consumption of the investment for a 1000 gpm centrifugal pump delivering water at 100 psig. (estimated total erected cost of $57,400).* Small fog spray water consumption of 0.25 gpm. Large fog spray water consumption of 2.5 gpm**
Small fog spray	$ 23	
Large fog spry (both versions)	$230	
Mobile fog spray	-0-	

*Cost escalated to January 1978, 25% contingency included. Reference 51.
**Reference 30.

Indirect costs charged to each spray device are: (a) construction overhead costs of 0.70 x (labor costs), (b) engineering costs of 0.14 (direct equipment costs), and (c) taxes and freight of 0.08 x (direct equipment costs).[51] Finally a contingency fee equal to 15 percent of total direct and indirect costs (excluding the auxiliary equipment investment which had its contingency added separately) is added. The indirect costs are shown on Table 20, "Summary of Total Estimated Costs for Charged Fog Spray Devices."

In addition to the capital investment associated with operating a charged fog spray device, there are utility requirements as well--electricity, water, and compressed air. Table 25 summarizes the utilities requirements for operation of a charged fog spray device all converted to an equivalent kilowatt basis. By far the largest energy requirements are for the compressed air used to atomize and project the spray droplets. The energy required to charge the droplets is minor and is not representative of the total energy consumption of the charged fog device.

TABLE 25. ENERGY CONSUMPTION FOR OPERATING A CHARGED FOG SPRAY DEVICE

Item	Energy Requirement, Equivalent Kilowatts per Charged Fog Device	Basis for Calculations
Pumping Energy for Water		Water from centrifugal pump at 100 psig discharge pressure, except hydraulically atomized version has 600 psig reciprocating pump; 0.25 gpm for small fog spray; 2.5 gpm for large fog spray; Mobile fog spray assumed to have same requirements as hydraulically atomized large fog spray.
Small fog spray	0.02	
Large fog spray (air atomized)	0.16	
Large fog spray (hydraulically atomized)	1.59	
Mobile fog spray	1.59	
Compression Energy for Air		Air from plant air compressor discharging at 100 psig; 10 scfm for small fog spray; 50 scfm for large spray; no air required for hydraulically atomized version; assumed no air required for mobile fog spray.
Small fog spray	2.66	
Large fog spray (air atomized)	13.32	
Large fog spray (hydraulically atomized)	-0-	
Mobile fog spray	-0-	
Electrical requirements for Charging		Charging requirement for small fog spray from manufacturer; requirement for large spray prorated by water consumption. Mobile spray requirement assumed equal to large fog spray.
Small fog spray	0.03	
Large fog spray (both versions)	0.30	
Mobile fog spray	0.30	
Total Equivalent Kilowatts		
Small fog spray	2.71	
Large fog spray (air atomized)	13.78	
Large fog spray (hydraulically atomized)	1.89	
Mobile fog spray	1.89	

*Reference 30.

5.0 WATER SPRAYS WITH ADDITIVES FOR CONTROLLING FUGITIVE EMISSIONS

It has been suggested that water sprays containing surface active agents would be more effective in collecting entrained dust than pure water sprays. The equipment for such a spray system would consist of hydraulic or air atomization spray nozzles, a reservoir and metering pump for injecting the additive into the water, and the appropriate connecting piping. Sprays with or without additives have been successful in reducing dust emitted from conveyor belts and are used in quarries and mining operations.[52-54]

There are conflicting reports of whether or not additives improve particle collection by water sprays. Much of the conflict comes from a confusion in the mechanisms working to reduce total particulate levels. There are two ways in which water suppresses particulate: (a) by wetting and immobilizing dust before becoming airborne and (b) by removing already suspended airborne particles.

To suppress dust formation, water is sprayed onto the surface of a solid material, for example ore concentrate on a conveyor belt. The water ideally spreads into the interstices of the solid, and wets the surface of fine particles thus making them adhere to the larger lumps of material. The wetted solid material then has less tendency to generate dust as it is handled since the small, easily entrained particles have been immobilized. However, since water has a very high surface tension (roughly 70 dynes/cm), it often is not effective in spreading into the solid material and forming a water film around dust particles. Instead it stays on the surface as thick droplets with resulting poor dust suppression. The high surface tension interferes with the wetting, spreading, and penetrating needed for suppression.

To improve the efficiency of suppression, various compounds known as surfactants, or wetting agents, are added to the water. These compounds are composed of a hydrophobic, or water-hating, group (usually a long chain hydrocarbon) and a hydrophilic, or water-loving, group (usually a sulfate, sulfonate,

hydroxide, or ethylene oxide). When mixed with water, surfactants concentrate at the air-water interface with the hydrophilic end aligning in the water layer and the hydrophobic portion of the molecule extending into the air layer. By preferentially aligning at the water-air interface, the surfactants can reduce the surface tension to around 30 dynes/cm and improve the wetting and penetration of the water. The levels of surfactant needed to effect such a surface tension reduction is very low--0.03 to 0.1 percent. Additives other than surfactants may be used in some cases to form a "crust" on storage piles, etc., and reduce windblown resuspension of dust.[56]

Water sprays are also sometimes used to try and remove particles which have already become airborne. The droplets from a water spray collect and coalesce the fine entrained particles and increase their settling rate. It has been suggested that surfactants would improve particle removal for this case also by allowing the dust particle to penetrate the water droplet more easily, however, there is little evidence that this occurs. Most investigators report surfactants do little to supress airborne respirable dust.[57] Walton and Woolcock[58] exposed equal size droplets to the same dust concentration; one droplet with a wetting agent and the other without. They found no significant difference in collection efficiency for the two drops. In a recent study, Woffinden et al[59] have reported only small effects of collection efficiency, if any, can be attributed to surface tension changes. Indeed, the effect of adding surfactant may be slightly unfavorable.[60]

In summary, water sprays with additives can be used to reduce suspension of hard-to-wet solids, but have an advantage over conventional water sprays only for reducing dust generation from dusts which have not already been suspended. Additives do not substantially improve the collection of particles which have already become airborne. Thus, they are not substitutes for charged fog spray applications. The addition of surfactants or other additives should be considered for such applications as conveying and storage bins where the product is not water sensitive and can be kept moist to reduce dust entrainment from the solid.

6.0 BUILDING EVACUATION FOR CONTROLLING FUGITIVE EMISSIONS

This section discusses the costs, energy consumption, and known applications of building evacuation as a means of controlling fugitive particulate emissions. The results of this section are used as a basis of comparison for the charged fog spray devices.

DESCRIPTION OF BUILDING EVACUATION

One method of eliminating fugitive particulate emissions from smelting operations which are inside a building is to install ductwork on the building roof and large fans which draw the particulate-laden gases from the building and pass them through a collection device. Typically, a baghouse is the control device selected for building evacuation. Any fugitive particulates escaping inside the smelter building are collected by the evacuation system and overall control efficiency for fugitive emissions is quite high for building evacuation--from 90 to over 95 percent.

While attractive from an environmental control viewpoint, building evacuation has several serious drawbacks. By enclosing the building, the emissions can only escape through the roof ducts and high levels of particulate, SO_2, etc., may build up inside the building in the workplace requiring breathing equipment and causing occupational health concerns. An evacuation system may collect enough gas to sufficiently ventillate the workplace overall and yet still have unacceptable local pollutant concentrations because of "dead spots" in the air flow pattern. Figure 10 illustrates this effect. In smelting operations, such dead spots may create excessive temperatures as well as high pollutant levels in some local areas.

A second drawback to building evacuation systems is the large airflow required and the attendant high energy consumption by the blower. As a general rule for controlling emissions with hoods, the closer the hood to the source, the less evacuation air is required. For the particular case of building evacuation, the intakes are located far from the particulate sources and large volumes of air with low particulate loadings are collected.

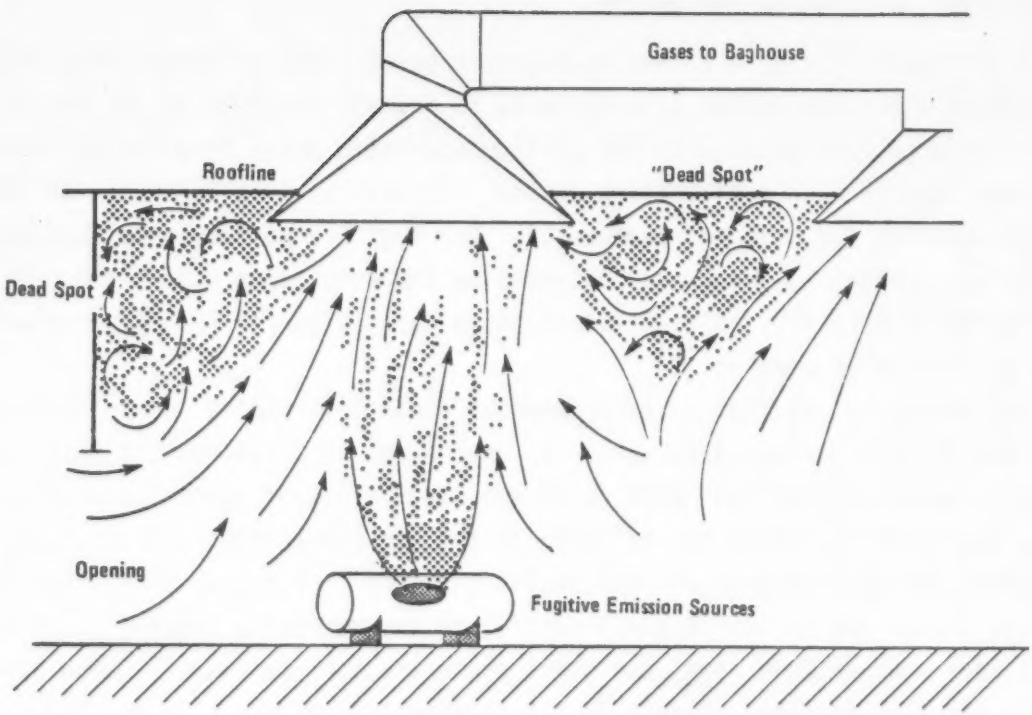


Figure 10. Schematic of "Dead Spots" in Building Evacuation System.

Building evacuation systems have been successfully applied to electric arc furnace melt shops in the iron and steel industry.[61,62] One converter building in the copper industry has been fitted with a building evacuation system[63] while there are no known large building evacuation systems in the lead smelting industry. The evacuation system in the copper smelting plant has caused severe heat and SO_2 levels in the upper areas of the building but this may be due to inadequate fan volumes and the difficulty in designing for good air flow patterns in a retrofitted application.

COST AND UTILITY CONSUMPTION FOR BUILDING EVACUATION

During some test work on an electric arc furnace building evacuation system, it was reported that a total of 1230 kW load was being drawn by the main baghouse fans treating 499,000 acfm of air at 95°F.[64] The reverse air fan for this system was rated at 150HP which corresponds to roughly an additional 125 kW load for a total of 0.00272 kW/acfm. - The baghouse had an air-to-cloth ratio of 2.3:1. No investment costs were given.

The retrofitted building evacuation system at the smelter cost approximately $8.5 million for a gas volume of about 600,000 acfm.[10] Three 700HP fans are used for this system for a utilities consumption of about 0.0029 kW/acfm. As was noted, the air is not changed frequently enough in this installation (2.7 minutes per air change) to prevent excessive local concentrations of pollutants.[63] An estimate was made by the Arizona Department of Health Services[63] for a "typical" smelter, as defined by the U.S. Bureau of Mines,[65] for installing building evacuation on a 100,000 ton per year smelter for the case of 1.5 air changes per minute. The air flow for this estimate was 2,200 kacfm.[66] Cost for this estimate are presented in Table 26.

For comparing building evacuation with charged fog spray devices, an initial investment of $6,808,000, (3.09 $/acfm) and utility consumption of 6000 kW were used for a building evacuation system for a converter building on a copper smelter. The costs and utilities for building evacuation in a lead smelter are similar to those for a copper smelter. However, it is felt that a larger volume of building space must be evacuated in a lead smelter. The evacuated building volume was assumed to be 150 percent of the building volume for copper smelting. Utility requirements were prorated directly by 1.5 to vie 9,000 kW, while capital costs were prorated using the 0.6 power rule to give $1.5^{0.6}$ x $6,808,000 = $8,683.000.

TABLE 26. CAPITAL AND OPERATING COST FOR BUILDING VENTILATION SYSTEM AT TYPICAL COPPER SMELTER*

		June 1978 Prices
Direct Plant Costs:		
Baghouse		$2,870,000
Fans and Motors		741,500
Electrical		178,500
Ductwork and Piping		179,000
Alterations to Building		40,000
Equipment Supports		60,000
	TOTAL DIRECT COST	$4,069,000
Indirect Costs:		
Engineering (14% T.D.C.)		$ 70,000
Field Expense (20% T.D.C.)		814,000
Contractors Fee (2.5% T.D.C.)		102,000
	TOTAL INVESTMENT	$5,555,000
Start-up (3.5% T.D.C.)		142,000
Contingency (20% T.I.)		1,111,000
	TOTAL CAPITAL	$6,808,000
Estimated Annual Operating Cost		$1,011,000

*Table from Reference 63.

7.0 COMPARISON OF CHARGED FOG SPRAYS WITH BUILDING EVACUATION

Estimates of the rough quantities of the small, large, and mobile charged fog sprays needed to control fugitive emissions in smelters are shown in Tables 27 and 28. The corresponding points of application are shown in Figures 11 and 12. These quantities are then used to estimate the cost and energy consumption of charged fog sprays applied throughout copper and lead smelters.

For application of charged fog sprays to a lead smelter, estimated capital investment is (24 large sprays x $7,091 each) + (4 mobile sprays x $3,514 each) + (29 small sprays x $4,364 each) for a total of $311,000. The utility consumption for the charged fog sprays in a lead smelter would be (24 large sprays x 13.78 kW each) + (4 mobile sprays x 1.89 each) + (29 small sprays x 2.71 kW each) for a total of 417 kW. For building evacuation, the estimated capital costs are $8,683,000 and the utility consumption is 9000 kW.

Capital investment (including installation and all auxiliary equipment) for application of charged fog sprays to a copper smelter is (24 large sprays x $7,091 each) + (6 mobile sprays x $3,514 each) + (40 small sprays x $4,364 each) for a total of $366,000. The utility consumption for the charged fog sprays in a copper smelter would be (24 large sprays x 13.78 kW each) + (6 mobile sprays x 1.89 kW each) + (40 small sprays x 2.71 kW each) for a total of 450 kW. For building evacuation, the corresponding costs are $6,808,000 and the utilities usage is 6,000 kW.

While both capital investment and energy consumption are higher for building evacauation, the reduction of total particulate and elemental lead emissions are also greater for building evacuation because of the higher collection efficiency and the larger number of sources covered by a building evacuation system.

Table 29 shows what are, by all accounts, rough estimates of the emission reductions expected from the application of charged fog sprays and the application of building evacuation. Estimated reductions are shown for both total particulate fugitive emissions and elemental lead fugitive emissions.

TABLE 27. POTENTIAL APPLICATIONS OF CHARGED FOG SPRAYS IN LEAD SMELTING[a]

Application	Number[b] Large	Mobile	Small	Comments
A-Railcar unloading	16			Installed as "curtain." 8 on each end of shed.
B-Conveyor transfer			3	
C-Conveyor transfer			3	
D-Conveyor transfer			3	
E-Mix tripper conveyor	2			Mounted to move with tripper.
F-Conveyor transfer			2	
G-Conveyor transfer			2	
H-Conveyor transfer			2	
I-Crusher discharge			4	
J-Pelletizing drum			4	
K-Conveyor transfer			2	
L-Conveyor transfer	2			Large sprays used to cool sinter
M-Roll grizzly discharge	2			Large spray used to cool sinter
N-Conveyor transfer			2	
O-Conveyor transfer			2	
P-Blast furnace tripper conveyor	2			Mounted to move with tripper.
Q-Front-end loader		4		
TOTAL	24	4	29	

[a]Refer to Figure 11 for locations of applications.

[b]Small charged spary coverage = 2 ft x 6 ft; Mobile charged spray coverage = 3 ft x 10 ft; large charged spray coverage = 6 ft x 20 ft.

TABLE 28. POTENTIAL APPLICATIONS OF CHARGED FOG SPRAYS IN COPPER SMELTING[a]

Application	Number[b] Large	Mobile	Small	Comments
A-Railcar unloading	16			Installed as "curtain." 8 on each end of shed.
B-Conveyor transfer			3	
C-Conveyor transfer			3	
D-Conveyor points in transfer house			6	
E-Ore bin tripper conveyor	2			Mounted to move with tripper.
F-Conveyor transfer			2	
G-Conveyor transfer			4	
H-Fine ore bin tripper conveyor	2			Mounted to move with tripper.
I-Drier discharge conveyor			2	
J-Conveyor transfer			2	
K-Concentrate stacker	2			
L-Dozer and front-end loader		6		Medium-size, mobile units mounted on dozer/loader
M-Conveyor transfer			4	
N-Conveyor transfer			4	
O-Tripper conveyor	2			
P-Conveyor transfer			2	
Q-Conveyor transfer			4	
R-Conveyor transfer			4	
TOTAL	24	6	40	

[a]Refer to Figure 12 for locations of applications.

[b]Small charged spray coverage = 2 ft x 6 ft; Mobile charged spray coverage = 3 ft x 10 ft; Large charged spray coverage = 6 ft x 20 ft.

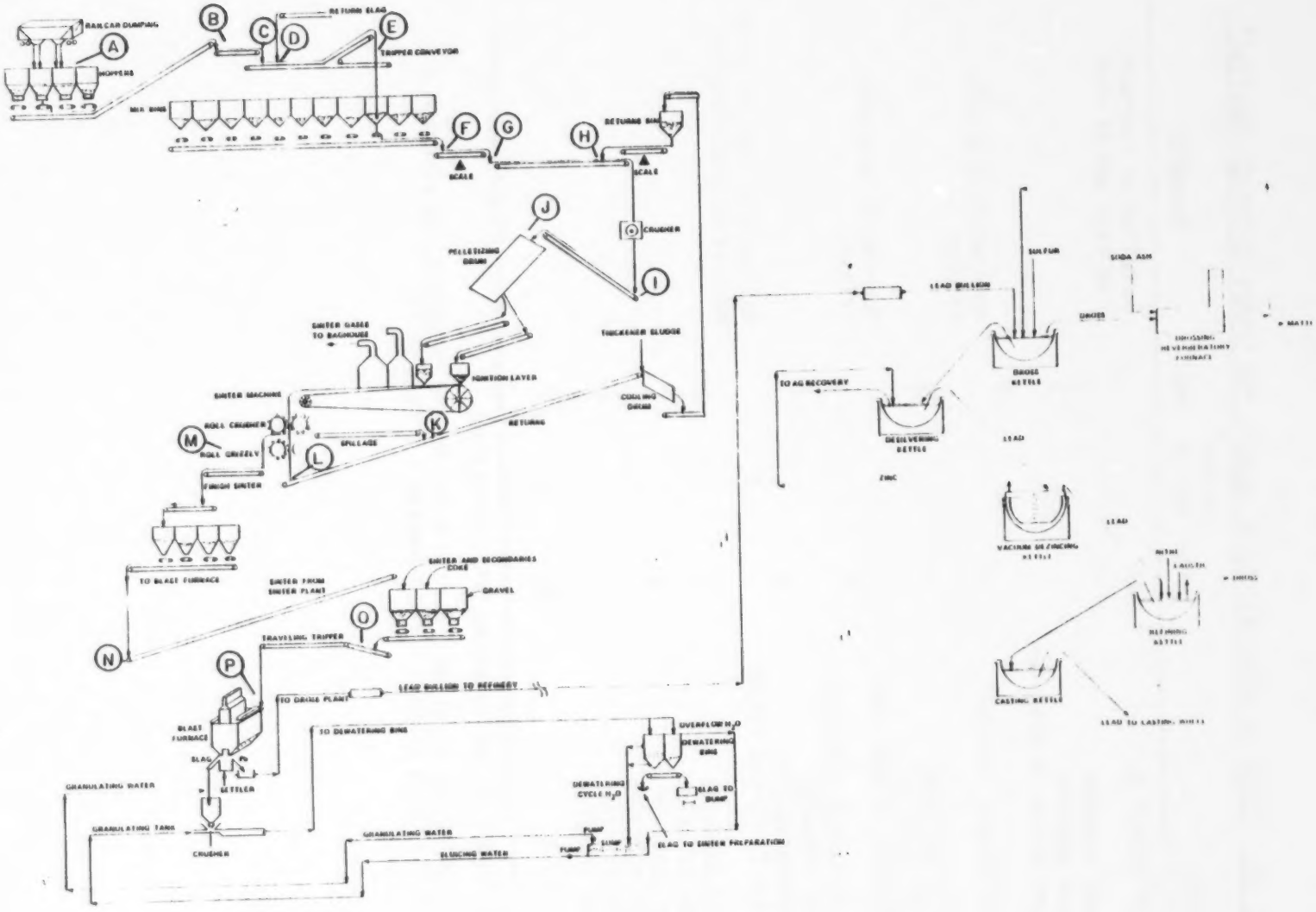


Figure 11. Charged Fog Spray Application Points in Lead Smelting.

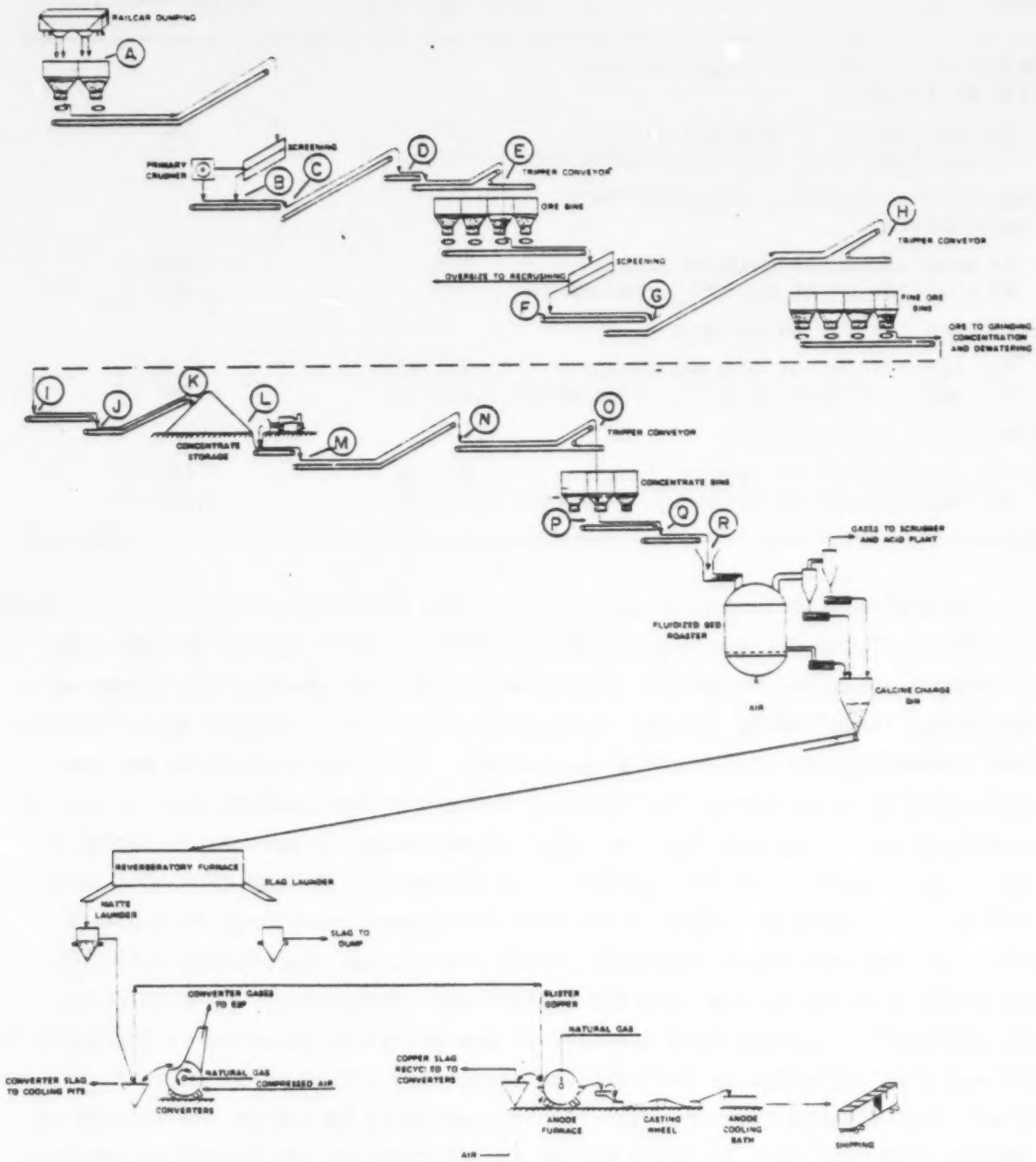


Figure 12. Charged Fog Spray Application Points in Copper Smelting.

TABLE 29. COMPARISON OF CHARGED FOG SPRAYS WITH BUILDING EVACUATION

Item	Lead Smelting	Copper Smelting
Reduction in fugitive total particulate emissions		
by application of charged sprays	30%	20%
by application of building evacuation	45%	40%
Reduction in fugitive elemental lead emissions		
by application of charged sprays	40%	35%
by application of building evacuation	75%	65%
Estimated capital investment		
for application of charged sprays	311 k$	366 k$
for application of building evacuation	8,683 k$	6,808 k$
Electrical requirement		
for application of charged sprays	417 kW	450 kW
for application of building evacuation	9,000 kW	6,000 kW

Several assumptions were made in compiling Table 29. The overall collection efficiency of the charged fog sprays was taken to be 60 weight percent; for building evacuation, 95 weight percent was used. The charged fog sprays were considered inapplicable for hot, turbulent areas such as molten metal transfer, lead sintering, and copper converter leakage. Building evacuation was not considered to be effective for reducing emissions from loading onto or out of storage piles. From the fugitive emission estimates, presented in Tables 2 and 3, the reduction of total particulate and elemental lead emissions were made source-by-source. Some of the emission source grouplings in Tables 2 and 3 included emissions from both inside and outside the process buildings--for example, handling and transfer of lead ore concentrate. In such cases, it was arbitrarily assumed that one-half of the emissions occurred in the building and would be collected by the building evacuation system at 95 percent efficiency. It was also assumed that an evacuation system could be put on the railcar unloading sheds but that it would not be as efficient as the system on the main buildings because of incomplete enclosure. A fifty percent overall capture and collection efficiency was used for railcar unloading emissions controlled by an evacuation system.

Superficially, the figures in Table 29 indicate charged fog sprays to be a more cost effective means for pollution control than building evacuation--10 to 20 k$ required for each percentage reduction in emissions by sprays versus 100 to 200 k$ required for each percent reduction by building evacuation. Similarly the electrical requirement is much lower for the charged fog sprays--15 to 30 kW for each percentage reduction versus 150 to 200 kW for the building evacuation system.

However, in spite of the apparent attractiveness of charged fog sprays, the authors feel that there are several practical problems which prevent them from supplanting building evacuation or secondary hooding as fugitive control techniques. The first and main objection is their limited applicability. Water sprays are only suitable when the process can tolerate water, when the emissions are from localized sources, when there is not a great deal of air turbulence and when the air is not at high temperatures. These limitations rules them out for such major sources of fugitive emissions as converter leakage, sintering, and metal tapping, pouring, and casting. A second major limit on charged fog spray control is the collection of the agglomerated particles. Throughout this treatment, it has been assumed that once suspended particles collide with a water droplet, they are permanently removed from the atmosphere. This is a valid assumption for such applications as conveyor transfer points in moderately still air where the agglomerated dust settles out and is returned to the process. However, when particles from, say, a railcar unloading station are contacted with spray droplets, they may settle out on the ground, dry out, and be reentrained.

One control option not yet considered in this report is localized hooding at fugitive emission sources. Figure 13 shows two options for controlling emissions from a railcar unloading station--a curtain of charged fog sprays and a push-pull collection system. This application gives a direct comparison of charged fog sprays with another control technique on the same source. Using recommended push-pull design procedures[67] and assuming the same utility requirements and cost per cubic foot as was used for building evacuation the following estimates were made: (a) 5.8 kW and $6,500 per lineal foot of opening for a push-pull system and (b) 2.3 kW and $1,900 per lineal foot for the

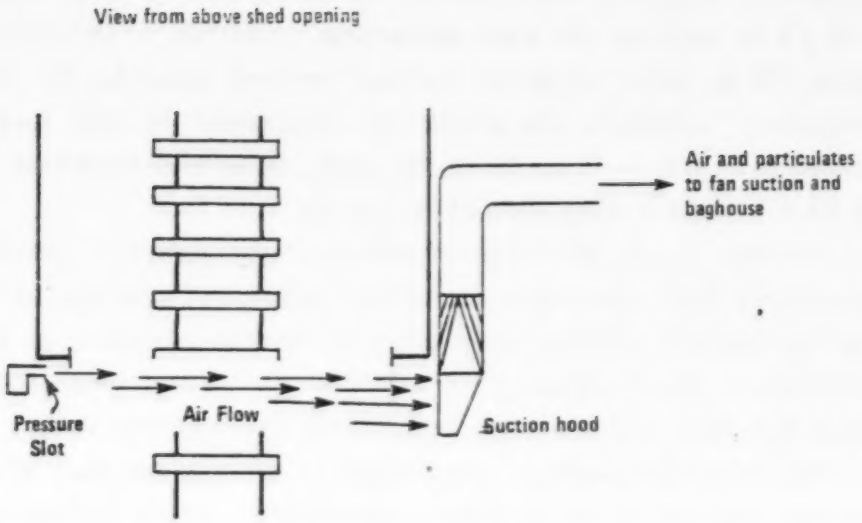

View from above shed opening
Air and particulates to fan suction and baghouse
Pressure Slot
Air Flow
Suction hood
Application of push-pull local hooding
Air, water, and electrical supply
Bank of charged fog sprays
Application of Charged Fog Spray Curtain.

Figure 13. Push-pull Local Hooding Versus Charged Fog Spray Curtain.

charged water spray curtain. Neglecting the potentially serious problem of particle reentrainment after spray evaporation, the charged sprays could in theory collect about half of the fugitive dust less expensively and with less energy than local hooding. However, it is pointed out that the sprays can only collect about half the particulate and if greater than fifty percent efficiency is needed, some other control method must be used in spite of any extra expense.

This report has treated building evacuation and charged fog sprays as either/or control techniques. It makes more sense to consider them as complementary control devices instead of mutually exclusive techniques. For high temperature, large scale, turblent emissions, either building evacuation or secondary hooding is required to collect the fugitive emissions. Charged fog sprays are better suited for smaller, localized emission sources. Two applications for which charged sprays may be particularly advantageous over other controls are: (a) mobile sources such as front-end loaders where any other type of control is impossible and (b) areas such as sanders or grinding wheels where personnel exposure must be reduced without impeding access.

A final caveat concerning the evaluation of charged fog sprays made in this report: only a screening evaluation has been made. To confirm their predicted performance in an industrial environment--where cross-drafts, reentrainment, and upsets occur--requires field tests and the measurement of actual reductions obtained with and without the device in operation.

8.0 REFERENCES

1. PEDCo - Environmental, Cincinatti, OH for U.S. EPA Contract No. 6802-2535. Task 1 for Metals and Inorganic Chemicals Branch, IERL-Cinn. Work in progress.

2. The Research Corporation of New England, Technical Manual for Measurement of Fugitive Emissions: volumes 1 through 3, U.S. Environmental Protection Agency Rep. Nos. EPA-600/2-76-089a (April 1976); EPA-600/2-76-089b (May 1976); and EPA-600/2-76-089c (May 1976).

3. PEDCo Environmental, Technical Guidance for Control of Industrial Process, Fugitive Particulate Emissions, U.S. Environmental Protection Agency, Research Triangle Park, N.C., Rep. No. EPA-450/3-77-010 (March 1977).

4. Environmental Protection Agency, Background Information for New Source Performance Standards: Primary Copper, Zinc, and Lead Smelters, vol.1 - Proposed Standards, U.S. Environmental Protection Agency, Research Triangle Park, N.C., Rep. No. EPA-450/2-74-002a (October 1974).

5. Gibson, F.W., "New Brick Lead Smelter Incorporates Forty Years of Technical Advances," Engineering and Mining Journal, pp. 62-67, (July 1968).

6. Constant, P., M. Marcus, and W. Maxwell, Sample Fugitive Lead Emissions from Two Primary Lead Smelters, U.S. Environmental Protection Agency, Research Triangle Park, N.C., Rep. No. EPA-450/3-77-031 (October 1977).

7. "Herculaneum: Tops in U.S. Refined Lead Output," Engineering and Mining Journal, pp. 87-91, (November 1976).

8. Katari, V., G. Isaacs, and T.W. Devitt, Trace Pollutant Emissions from the Processing of Metallic Ores, U.S. Environmental Protection Agency, Washington, D.C., Rep. No. EPA-650/2-74-1151 (October 1974).

9. Daugherty, D.P. and D.W. Coy, "Trip Report-5/11/78 Visit to St. Joe Lead Company, Herculaneum Lead Smelter, Herculaneum, Missouri, Research Triangle Institute, Research Triangle Park, N.C.

10. Environmental Protection Agency, Evaluation of Zinc Fuming Furnace Emissions, Bunker Hill Lead Smelter, Kellogg, Idaho, U.S. Environmental Protection Agency, Office of Enforcement, National Enforcement Investigations Center, Denver, CO., Rep. No. EPA-330/2-77-010 (April 1977).

11. Charles River Associates, Inc., Economic Impact of the Proposed EPA National Ambient Air Quality Standard for Lead: Background Support Document, Charles River Associates, Inc., Cambridge, Mass. CRA Report #398, pp. 37-45, (March 1978).

12. Bohn, R., T. Cuscino, Jr., and C. Cowherd, Jr., Fugitive Emissions from Integrated Iron and Steel Plants, U.S. Environmental Protection Agency, Washington, D.C., Rep. No. EPA-600/2-78-050.

13. Shearer, D.L. and E.J. Brookman, Impact Analysis of EPA Proposed National Ambient Air Quality Standard for Lead on Primary and Secondary Lead Smelters, The Research Corporation of New England, Wethersfield, Conn. (February 1978).

14. Jones, H.R., Pollution Control in the Nonferrous Metals Industry: 1972, Noyes Data Corporation, Park Ridge, N.J., p. 145, (1972).

15. Dorn, C.R., J.O. Pierce, G.R. Chase, and P.E. Phillips, "Environmental Contamination by Lead, Cadmium, Zinc, and Copper in a New Lead-Producing Area," Environmental Research 11, No. 2, pp. 159-172, (April 1975).

16. Research Triangle Institute, Air Pollution from Lead and Zinc Processing Plants: Trepca, Yugoslavia, Research Triangle Institute, Research Triangle Park, N.C., Contract No. 68-02-1325, Task 47, p. 14.

17. Harris, D.B., and D.C. Drehmel, "Fractional Efficiency of Metal Fume Control as Determined by Brink Impactor," presented at 66th Annual Meeting of the Air Pollution Control Association, Chicago, Illinois. June 24-28, (1973).

18. Dorn, D.R., J.O. Pierce, II, P.E. Phillips, and G.R. Chase, "Airborne Pb, cd, Zn and Cu Concentration by Particle Size Near a Pb Smelter." Atmospheric Environment, v. 10, pp. 443-445 (1976).

19. Environmental Protection Agency, Background Information for New Source Performance Standards, U.S. Environmental Protection Agency, Research Triangle Park, N.C., Rep. No. EPA-450/2-74-002a, (October 1974).

20. Weisenberg, I.J. and J.C. Serne, Design and Operating Parameters for Emission Control Studies, Volumes a through k, U.S. Environmental Protection Agency, Washington, D.C., Rep. Nos. EPA-600/2-76-036a through k, (February 1976).

21. Daugherty, D.P., and D.W. Coy, "Trip Report - 7/28/78, Visit to Kennecott Copper Corporation, Hayden Smelter, Hayden, Arizona," Research Triangle Institute, Research Triangle Park, N.C. (1978).

22. "Fugitive Arsenic Emissions From Copper Smelters," Contracted by Office of Air Quality Planning and Standards, Emissions Standards and Engineering Division, U.S. Environmental Protection Agency, Durham, N.C., (work in progress).

23. "Components of Concentrates Processed in the U.S. "Summary of confidential information in Research Triangle Institute files.

24. Wagner, W.L., "Environmental Conditions in U.S. Copper Smelters," HEW, NIOSH, Division of Technical Services, Salt Lake City, Utah, HE20.7102:C 79, HEW Publication No. NIOSH 75-158 (April 1975).

25. Research Triangle Institute, "Air Pollution Caused by Copper Metallurgy in Bor: Summary Report," Research Triangle Institute, Research Triangle Park, N.C., EPA Contract No. 68-02-1325, Task 47 (November 1976).

26. Thompson, G.S., Jr. and G.B. Nichols: "Experience with Electrostatic Precipitators as Applied to the Primary Copper Smelting Reverberatory Furnace" in Proceedings: Particulate Collections Problems Using ESP's in the Metallurgical Industry. EPA-600/2-77-208 (NTIS PB 274 017/AS), U.S. Environmental Protection Agency, Research Triangle Park, N.C. pp. 234-251 (1977).

27. Wood, C.W. and T.H. Nash III, "Copper Smelter Effluent Effects on Sonoran Desert Vegetation," Ecology, v 57, pp. 1311-1316 (1976).

28. Hoenig, Stuart A., Use of Electrostatically Charged Fog for Control of Fugitive Dust Emissions, U.S. Environmental Protection Agency Rep. No. EPA-600/7-77-131, (November 1977).

29. Hassler, H.E., "A New Method for Dust Separation Using Autogenous Electrically Charged Fog," Journal of Powder and Bulk Solids Technology, v.2, n.1, pp. 10-14 (Spring 1978).

30. Communications with E.W. Drum, Manager of the Air Pollution Control Department of Ransburg Electrostatic Equipment, Indianapolis, IN (May 1978).

31. Shafrir, U. and T. Gal-Chen, "A Numerical Study of Collision Efficiencies and Coalescence Parameters for Droplet Pairs and Radii up to 300 Microns," Journal of the Atomospheric Sciences, v.28, pp. 741-751, (July 1971).

32. Slinn, W.G.N., and J.M. Hales, "A Reevaluation of the Role of Thermophoresis as a Mechanism of In-and Below-Cloud Scavenging "Journal of the Atomospheric Sciences, v.28, pp. 1465-1471 (November 1971).

33. Lai, Kuo-Yann, N. Dayan, and M. Kerker, "Scavenging of Aerosol Particles by a Falling Water Drop," Journal of the Atmospheric Sciences, v. 35, pp. 674-682, (April 1978).

34. Wang, P.K, and H.R. Pruppacher, "An Experimental Determination of the Efficiency with Which Aerosol Particles are Collected by Water Drops in Subsaturated Air," Journal of the Atmospheric Sciences, v. 34, pp. 1664-1669, (October 1977).

35. Grover, S.N., H.R. Pruppacher, and A.E. Hamielec, "A Numerical Determination of the Efficiency with Which Spherical Aerosol Particles Collide with Spherical Water Drops Due to Inertial Impaction and Phoretic and Electrical Forces," Journal of the Atmospheric Sciences, v. 34, pp. 1655-1663, (October 1977).

36. Ranz, W.E., "On the Evaporation of a Drop of Volatile Liquid in High-Temperature Surroundings," Transaction of the ASME, pp. 909-913, (1956).

37. Ranz, W.E. and W.R. Marshall, Jr., "Evaporation from Drops," Chemical Engineering Progress, v. 48, pp. 141-173, (1952).

38. Marshall, W.R., Jr., "Evaporation from Drops and Sprays," Atomization and Spray Drying, Chemical Engineering Monograph Series No. 2, v. 50 (1954).

39. Masters, K. Spray Drying, 2 ed. John Wiley and Sons, New York, (1956).

40. Melcher, J.R. and K.S. Sachar, "Charged Droplet Technology for Removal of Particulates from Industrial Gases," Rep. No. APTD-0868, PB-205 187 (August 1971).

41. Melcher, J.R. and K.S. Sachar, "Charged Droplet Scrubbing of Submicron Particulate," U.S. Environmental Protection Agency, Washington, D.C., Rep. No. EPA-650/2-74-075, PB-241 262, (August 1974).

42. Doyle, A., D.R. Moffett, and B. Vonnegut, "Behavior of Evaporating Electrically Charged Droplets," Journal of Colloid Science, v. 19, pp. 136-143, (1965).

43. Koscianawski, J.R., L. Koscianowski, and E. Szezepankiewicz, "Effects of Filtration Parameters on Dust-cleaning Fabrics," Report prepared for U.S. Environmental Protection Agency, Contract No. P-5-533-3, EPA Project Officer: James H. Turner, Industrial Environmental Research Laboratory, Research Triangle Park, N.C. (December 1976).

44. Walkenhorst, W., "Deliberations and Studies on the Filtration of Dust-laden Gases With Special Allowance for Electric Forces," Staub-Reinhalt Luft, v. 29, no. 12 (December 1969).

45. George, H.F., and G.W. Poehlein, "Capture of Aerosol Particles by Spherical Collectors--Electrostatic, Inertial, Interception, and Viscous Effects," Environmental Science and Technology, v. 8, n.1, pp. 46-49 (January 1974).

46. Cheng, L., "Collection of Airborne Dust by Water Sprays," Industrial Engineering/Chemistry, Process Design and Development, v. 12, n.3, pp. 221-225, (1973).

47. Walton, W.H. and A. Woolcock," The Suppression of Airborne Dust by Water Sprays," International Journal of Air Pollution, v. 3, pp. 129-153, (1960).

48. Courtney, W.G., and L. Cheng, "Control of Respirable Dust by Improved Water Sprays," Respirable Dust Control, Proceedings: Bureau of Mines Technology Transfer Seminars, U.S. Bureau of Mines Information Circular No. IC/8753, U.S. Department of the Interior, Washington, pp. 92-108, (1977).

49. Personal Communication, Bete Fog Nozzle, Inc., Greenfield, MA. (1978).

50. Personal Communication with Ken Winter; Facet Enterprises, Inc.; Industrial Filter Products Marketing; P.O. Box 50096, Tulsa, OK 74150, (1978).

51. Guthrie, Kenneth M., Process Plant Estimating, Evaluation, and Control, Craftsman Book Company of America, Solana Beach, Calif. (1974).

52. Godfrey, Robert S., editor-in-chief, Building Construction Cost Data 1978, 36th annual edition, Robert Snow Means Company, Dusbury, Mass. (1977).

53. Johnson March Corporation, Dust Control News, Vol. No. 1, Philadelphia (Fall 1978).

54. Emmerling, J.E., and R.J. Seibel, "Dust Suppression With Water Sprays During Continuous Coal Mining Operations," U.S. Bureau of Mines Report of Investigation 8064, Washington (1975).

55. Courtney, W.G., N.I. Jayaraman, and P. Behum, "Effect of Water Sprays for Respirable Dust Suppression With a Research Continuous-Mining Machine," U.S. Bureau of Mines Report of Investigation 8283, Washington (1978).

56. Dean, K.C., R. Havens, and M.W. Glantz, "Methods and Costs for Stabilizing Fine-Mineral Wastes." U.S. Department of the Interior, Bureau of Mines, R.I. 7894, (1974).

57. Kobrick, T., "Water as a Control Method, State of the Art, Sprays and Wetting Agents," Paper in Proceedings of the Symposium on Respirable Coal Mine Dust, Washington, D.C., November 3-4, 1969, comp. by R.M. Gooding. Bureau of Mines IC 8458, pp. 123-133, (1970).

58. Walton, W.H., and A. Woolcock, "The Suppression of Airborne Dust by Water Spray," International Journal of Air Pollution, v. 3, pp. 129-153 (1960).

59. Woffinden, G.J., G.R. Markowski, and D.S. Ensor, Effects of Interfacial Properties on Collection of Fine Particles by Wet Scrubbers, U.S. Environmental Protection Agency, Washington, Rep. No. EPA-600/7-78-097 (June 1978).

60. Emory, S.F., and J.C. Berg, "Surface Tension Effects on Particle Collection Efficiency," Appendix to Reference 59.

61. Kaercher, L.T. and J.D. Sensenbaugh, "Air Pollution Control for an Electric Furnace Melt Shop," Iron and Steel Engineer, pp. 47-51, (May 1974).

62. Research Triangle Insitute, "Trip Report: Crucible, Inc, Midland, PA", (August 4, 1977).

63. Billings, C.H., "Second Annual Report on Arizona Copper Smelter Air Pollution Control Technology," Arizona Department of Health Services, Phoenix, AZ (April 1978).

64. Roy F. Weston, Inc., "Source Testing Report: The Babcock and Wilcox Company Electric Arc Furnace, Beaver Falls, PA," EPA Contract No. 68-02-0240, Task No. 2, FTS No. 73-ELC-1 (January 1973).

65. Hayashi, M., H. Dolezal, and J.H. Bilbrey, Jr. Cost of Producing Copper From Chalcopyrite Concentrate as Related to SO_2 Emission Abatement, U.S. Bureau of Mines Report of Investigations No. RI/7957, U.S. Department of the Interior, Washington (1974).

66. Personal Communication with C.H. Billings, Arizona Department of Health Services, Phoenix, AZ (November 1978).

67. American Conference of Governmental Industrial Hygienists, Industrial Ventilation, 9th ed., Edward Brothers, Inc., Ann Arbor, MI, (1966).